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Techno-Economic Assessment of Deep Electrification of Passenger Vehicles in India

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Executive Summary

Introduction

In India, there is growing interest among policymakers, planners, and regulators in aggressive electrification of passenger vehicles. For example, Piyush Goyal, the Minister of State for India's Ministries of Coal, Power, and New and Renewable Energy, has announced an aspirational goal of full electrification of passenger vehicle sales by 2030. In 2012, India announced the National Mission on Electric Mobility, setting a countrywide goal of deploying 6–7 million hybrid and electric vehicles by 2020. Given that lithium ion battery costs have dropped 80% in the last six years and continue to fall, large-scale electrification of light duty vehicles is an attainable goal for India. This report assesses the system-level techno-economic impacts, if all light duty passenger vehicle (i.e. cars and two-wheelers) sales in India by 2030 were battery electric vehicles (BEVs).

Methods and Assumptions

We conduct the analysis using three simulation-optimization models: (a) the Plug-in Electric Vehicles Infrastructure (PEVI) model, an agent-based travel and charging demand model that simulates BEV driving and charging behavior, (b) PLEXOS, an industry-standard simulation model for least-cost investment planning and economic dispatch of the power system, and (c) the Economic and Environmental Impacts model, a spreadsheet-based tool that assesses the impact on emissions, oil imports, and utility finances.

Using projections of travel demand in 2030, total BEV penetration and efficiency, and agent-based modeling of charging behavior, PEVI estimates the BEV charging load for each hour of the year. Using official government data and historical trends, we project hourly electricity demand in the country from sources other than BEVs. We then simulate the 2030 power system in India using certain assumptions on operational constraints and by creating the following two scenarios for the electricity generation capacity mix: (a) the Business as Usual (BAU) scenario, which includes the new electricity generation investments as identified in India's 12th 5-year plan (up to 2022) and National Electricity Plan (up to 2027), extrapolated to 2030, and (b) the NDC Compliant scenario, which includes the aggressive renewable energy (RE) targets committed to by India in its Nationally Determined Contribution (NDC) for the Paris Climate Agreement (100 GW of solar and 60 GW of wind by 2022), extrapolated to 2030. In each scenario, we simulate hourly economic grid dispatch in 2030 to assess the hourly grid emission factors.

Travel Demand

We assume that the travel demand in the rest of the country by 2030 is identical to the current travel demand in the city of Delhi (National Capital Territory). We assume the average vehicle kilometers traveled (VKT) to be 12,800 km/yr for two-wheelers and 12,200 km/yr for cars by 2030. These numbers are similar to current annual VKT in several developed and emerging economies, including China.

Vehicle Sales and Stock

For 100% vehicle sale electrification by 2030, two-wheeler BEV sales would be 32 million/yr, and BEV car sales would be 10 million/yr. Based on a simple stock turnover model with a vehicle life of 15 years, BEVs would be 29% of the total active two-wheeler stock and 44% of the total active car stock by 2030. If the same trend continues, full vehicle stock electrification would be expected by the mid-2040s.

Vehicle Efficiencies and Costs

We split cars into three different classes: subcompact hatchbacks, compact sedans, and vans / multi-use vehicles (MUVs). For each vehicle class, we take the most popular model in 2015 and use manufacturer-labeled fuel efficiency and costs. We make adjustments for BEV sedans and MUVs, because they are not widely available in India. We assume that, by 2030, vehicle efficiencies improve and costs change; the rate of improvement is taken from a study by the U.S. National Research Council.

Key Results

BEV Financing and Operating Costs Are Lower than Gasoline Costs

BEV owners can benefit significantly when they switch from internal combustion engine (ICE) vehicles. Figure 1 compares the annualized incremental cost of BEVs (i.e., annualized incremental capital cost and total annual electricity cost) with the total annual fuel cost of ICE vehicles for subcompact hatchbacks. The annualized capital cost is estimated using a preferential interest rate of 6%. The difference in the ICE fuel cost and the total incremental cost of BEVs is the net BEV owner's benefit. Between 2015 and 2030, the incremental capital cost of BEVs over ICE vehicles drops by over 60%–70%. By 2030, the net BEV owner's benefit is more than Rs 9,200/yr, and BEVs have a simple payback period of 5 years. In the initial years, the owner's benefit is highly sensitive to the interest rate assumption.

Another important determinant of BEV cost-effectiveness is the distance traveled. As VKTs increase, BEVs become more financially attractive. For high VKTs (above 18,000 km/yr), the net consumer benefit is as high as Rs 20,000/yr by 2030. For low VKTs (less than 6,500 km/yr), BEVs may not be fully cost-effective. Since taxis (including shared-service vehicles such as Uber or Ola vehicles) have much higher VKTs than other passenger vehicles, they could be among the first candidates for BEV adoption. Moreover, they could be converted as a fleet, thereby significantly reducing transaction and program-administration costs. For vehicles with low VKTs, BEV cost-effectiveness depends largely on the interest rate assumption. Thus a BEV bulk procurement program with preferential financing (similar to Energy Efficiency Services Limited's efficient appliance programs) is crucial for early adoption. Such programs could be run by a third party and may not need government financial support.

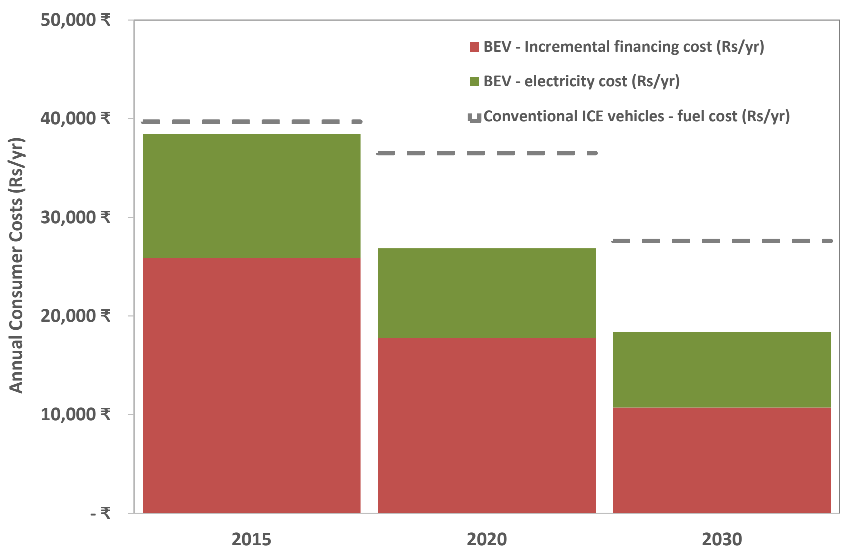

Figure 1: Annualized incremental cost of BEVs and annual fuel cost of ICE vehicles for subcompact hatchbacks

100% BEV Sales Will Only Add 6% to Peak Electricity Load

Despite aggressive vehicle electrification, the additional load added from BEV charging by 2030 is only 82 TWh/yr, or 3.3% of the total electricity load in India. Peak BEV charging load is 23 GW, which is about 6% of the total peak load by 2030 (402 GW). This is mainly because: (a) in most urban areas of India, the rapid increase in electricity demand from numerous other end uses (particularly air conditioners) will be very large over the next 15–20 years, (b) vehicle penetration by 2030 is dominated by two-wheelers that require much less energy than cars, and (c) the overall vehicle penetration is expected to be significantly lower than the penetration in other industrialized or emerging economies. Total energy consumption by BEVs depends on several key assumptions such as vehicle sales growth, VKTs, and BEV efficiency. Even if all parameters are varied by +/-25%, the overall range for BEV energy consumption in 2030 is 62–103 TWh/yr (2–4% of the non-BEV energy load) and for peak load is 19–39 GW (5–10% of the non-BEV peak).

Utility Revenue from BEV Charging Can Eliminate Financial Deficits

Although the additional load due to BEV charging is minor, it could still provide a valuable additional revenue source for the financially distressed distribution utilities (Figure 2). Assuming a marginal electricity tariff of Rs 9/kWh, BEV charging load could earn about Rs 70,000 Cr/yr ($10 billion/yr) of additional revenue for utilities by 2030. In 2014, the total utility financial deficit was Rs 62,000 Cr/yr, and total government subsidy support to utilities was about Rs 36,000 Cr/yr.

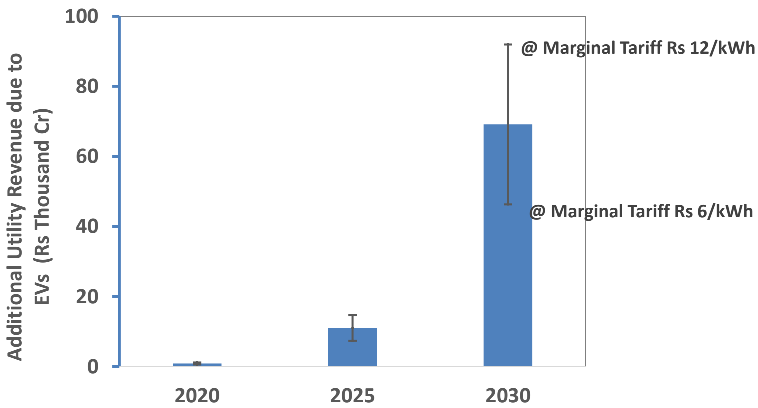

Figure 2: Additional utility revenue due to BEV charging load (Rs thousand Crore)

BEVs Will Lower CO_2 Emissions Significantly

Using the temporally explicit grid emission factors for each vehicle category (output of PLEXOS simulations), Figure 3 shows the per-kilometer CO_2 emissions for ICE vehicles and BEVs. In the NDC Compliant scenario, BEVs reduce emissions by over 40%–50%. Even if none of the decarbonization measures in the BAU plan materialize and the grid in 2030 remains as coal heavy as it was in 2015, BEVs still reduce per-kilometer CO_2 emissions by 20%–30%. If vehicle electrification continues beyond 2030, it would lead to a reduction of about 600 million ton/yr of CO_2 emissions by 2050.

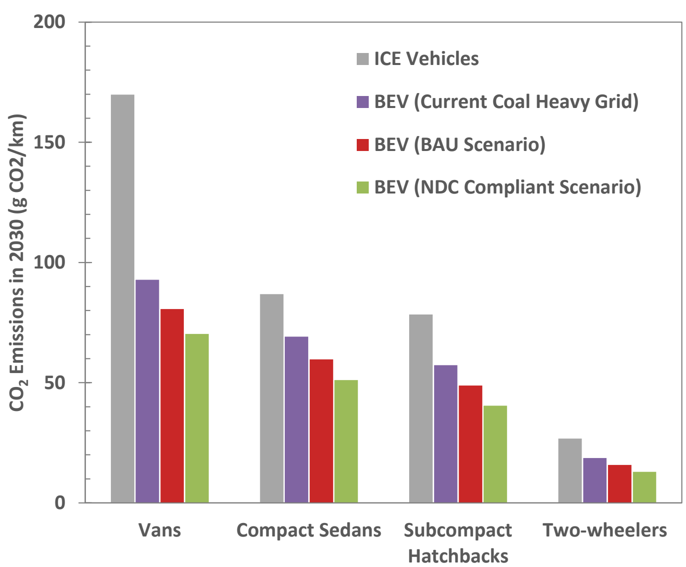

Figure 3: Per-kilometer CO_2 emissions from ICE vehicles and BEVs in 2030

BEVs Will Substantially Reduce Crude Oil Imports

By 2030, BEVs can reduce total crude oil consumption by 360 million barrels/yr (15% of total). Assuming a conservative crude oil price of $40/barrel, this translates to reducing oil imports by $7 billion/yr by 2030 (about Rs 50,000 Cr/year). If all vehicle sales by 2030 and beyond are BEVs, all ICE vehicles purchased before 2030 retire by the mid-2040s, and total crude oil consumption by the passenger vehicle fleet becomes zero. By 2050, total avoided crude oil consumption would be 2,695 million barrels/yr (about 60% of total), leading to savings of $100 billion/yr (Rs 700,000 Cr/yr) in oil imports.

Smart Charging of BEVs Can Enable Cost-Effective RE Integration

BEV charging load could be shifted to a different time of the day to reduce total system cost and help RE grid integration. Such load shifting is called smart charging. Figure 4 shows BEV charging profiles with and without smart charging for the NDC Compliant scenario in May 2030 as well as average hourly total RE generation (solar and wind). The BEV charging load shifts almost entirely to the daytime to match solar generation; this can avoid RE curtailment or inefficient operation of thermal power plants during high-RE periods. In addition, because most of the BEV charging occurs during the solar-generation hours, its temporally explicit grid emission factors are lower than in the fixed (non-smart) charging case.

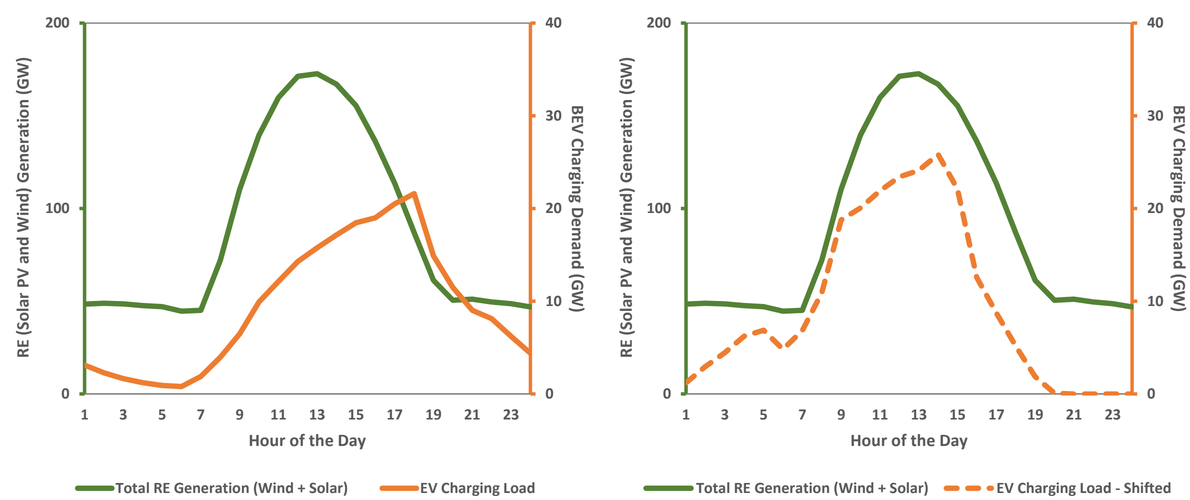

Figure 4: Average hourly RE generation and BEV charging load – NDC Compliant scenario (May 2030)

<u>Conclusion</u>

In summary, we find that large-scale electrification of passenger vehicles in India can deliver significant benefits to BEV owners, provide additional revenue to utilities without a major increase in electricity demand, reduce total electric-system costs and help integrate RE into the grid via smart charging, and contribute substantially to India's climate mitigation and energy security portfolio. One important assumption in our study is the ability of all BEV owners to access public charging infrastructure. Deployment of such infrastructure would be capital intensive, but it could be financed using the additional revenue from BEV charging. In addition, it is likely that the BEV charging load could have significant impacts on local distribution networks. The problem may worsen if the BEV hotspots coincide with solar photovoltaic (PV) hotspots and may require significant distribution system upgrades. We intend to address all of these issues in our future work.

Techno-Economic Assessment of

Deep Electrification of Passenger Vehicles in India

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1. Introduction

In India, there is growing interest among policymakers, planners, and regulators in aggressive electrification of passenger vehicles. For example, Piyush Goyal, the Minister of State for India's Ministry of Coal, Power, New and Renewable Energy, announced an aspirational goal of converting all vehicle sales in India to battery-electric vehicles (BEVs) by 2030 (Economic Times, 2016). In 2012, India announced the National Mission on Electric Mobility, which set a countrywide goal of deploying 6 to 7 million hybrid and electric vehicles (EVs) by 2020 (DHI, 2012). Given the deep reduction in battery and electric vehicle costs in recent years, these goals are not outside the realm of possibilities. A major policy motivation for transport electrification is reducing India's oil import dependence. While electrifying transportation will reduce India's oil imports, it is not clear if switching to electric vehicles will lower greenhouse gas (GHG) emissions. In fact, many hold the view that electric vehicles will increase India's GHG emissions owing to the country's high dependence on coal for electricity production (Doucette & McCulloch, 2011). Also, given the chronic power shortages in the country, policymakers have significant concerns regarding the capability of the grid to reliably handle additional load from numerous BEVs.

Numerous studies have assessed the economic and environmental impacts of BEVs in the U.S. and European contexts. See, for example, (Campanari, Manzolini, & Garcia de la Iglesia, 2009; Hawkins, Gausen, & Strømman, 2012; Kennedy, Ibrahim, & Hoornweg, 2014; MacPherson, Keoleian, & Kelly, 2012; McCleese & LaPuma, 2002). However, there is very limited literature on this topic for India. We have found only one peer-reviewed study that models the GHG emissions associated with BEVs in India (Doucette & McCulloch, 2011). Doucette and McCulloch (2011) find that BEVs will increase CO_2 emissions in India relative to conventional vehicles. However, their analysis uses the grid emission factors from 2010, and it is not temporally explicit with respect to electric vehicle trips or the power system. Under its Nationally Determined Contribution (NDC) for the Paris Climate Agreement, India has already committed to reduce the carbon intensity of its power system significantly. Also, temporally explicit assessments are more appropriate for informing policy in India, where massive power system expansion will be needed over the next decade regardless of BEV power demand (Abhyankar et al., 2013a). Of the few other studies that do model temporal power generation and charging demand variation, none cover India (Axsen, Kurani, McCarthy, & Yang, 2011; EPRI and NRDC, 2007; Hadley & Tsvetkova, 2009; Jansen, Brown, & Samuelsen, 2010; McCarthy & Yang, 2010; Parks, Denholm, & Markel, 2007). Similarly, several studies have assessed the impact of electric vehicles on utility load and energy costs as well as how "smart" or "optimal" charging of electric vehicles can help renewable energy (RE) grid integration and overall ancillary services costs in the U.S. and European contexts (Kempton & Letendre, 1997; Lopes, Soares, & Almeida, 2011; Lund & Kempton, 2008; Rahman & Shrestha, 1993; Rotering & Ilic, 2011). Unfortunately, no such studies could be found for India.

The objective of this report is to assess the effect of full electrification of passenger vehicle (i.e. cars and two-wheelers) sales in India by 2030 on key stakeholders, including BEV owners, electric utilities, and the government. Specifically, we address the following questions:

(a) How does the total vehicle ownership cost of BEVs compare with the cost of conventional vehicles?
(b) What is the additional load due to BEV charging?
(c) What is the impact on power-sector investments, costs, and utility revenue?
(d) How can smart BEV charging help RE grid integration?
(e) What is the impact on crude oil imports?
(f) What is the impact on GHG emissions?

Note that we assess full vehicle sales electrification to understand whether the additional power requirement and related infrastructure could be a significant barrier at such a scale of penetration. Further, it provides somewhat of an upper bound on the peak load or additional revenue that the power sector could earn due to vehicle electrification. Also, an implicit assumption in the study is that the appropriate policies and incentives are in place for such aggressive electrification of the passenger vehicle fleet; assessing the feasibility or risks of our pathway is out of the scope of this report.

The remainder of the report is organized as follows. Section 2 describes our modeling method, key assumptions, and data. Section 3 shows the key results of our analysis. Section 4 concludes and suggests policy implications.

2. Methods, Data, and Assumptions

We conduct the analysis using three simulation-optimization models: (a) the Plug-in Electric Vehicles Infrastructure (PEVI) model, an agent-based BEV travel and charging demand model that simulates BEV driving and charging behavior, (b) PLEXOS, an industry-standard simulation model for least-cost investment planning and economic dispatch of the power system, and (c) the Economic and Environmental Impacts model, a spreadsheet-based tool that assesses the impact on emissions, oil imports, and utility finances. In this section, we describe our modeling approach, key features of the models, assumptions, and data. Figure 5 summarizes our overall modeling approach.

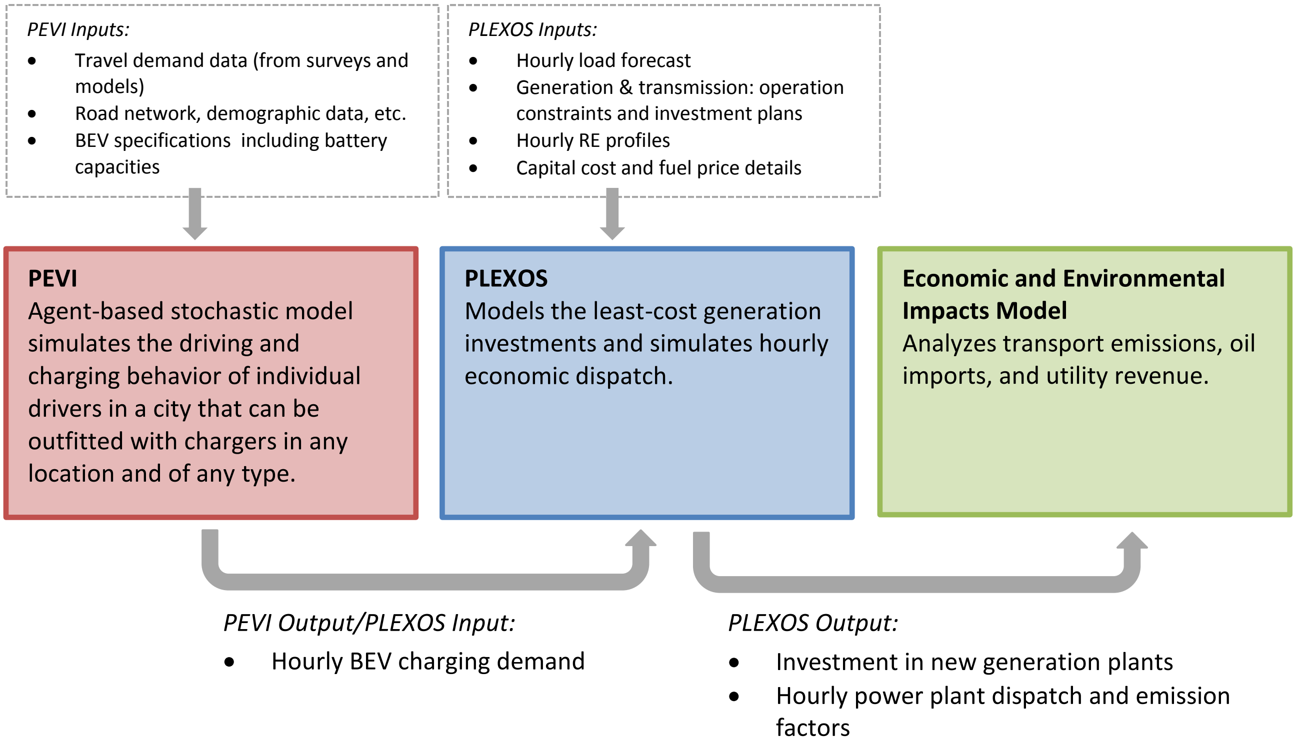


Figure 5: Summary of the modeling approach

Using the assumptions for travel demand in 2030 and total BEV penetration and efficiency as well as agent-based modeling of the charging behavior, PEVI estimates the BEV charging load for each hour of the year. Using official government data and historical trends, we project hourly electricity demand in the country from sources other than BEVs. We then simulate the 2030 power system in India using certain assumptions about operational constraints and by creating the following two scenarios for the generation capacity mix:

(a) Business as Usual (BAU), which includes the new electricity-generation investments identified in the National Electricity Plan (NEP) up to 2027, extrapolated to 2030.

(b) NDC-Compliant Scenario, which includes the aggressive RE targets committed to by India in its NDC (100 GW of solar and 60 GW of wind by 2022), extrapolated to 2030.

In each scenario, we simulate least-cost generation capacity expansion and hourly economic grid dispatch so that the electricity demand (non-BEV as well as BEV) is fully met. We then use the capacity expansion and hourly power plant operation results to (a) estimate the temporally explicit grid emission factors, which are in turn used to assess the BEV emissions, (b) assess how smart BEV charging could reduce the overall system cost, and (c) assess the total BEV charging load and the impact on utility finances. We also conduct sensitivity analyses to assess the robustness of our findings given the uncertainties in multiple key parameters.

Note that our modeling approach is data intensive. While we could build a national power system model for India, we only had access to detailed travel demand data for the National Capital Territory (NCT) region of Delhi.[1] We assume that the travel demand in the rest of the country by 2030 is identical to that in the NCT region. For the following four reasons, we believe this assumption is valid for the levels of vehicle electrification that we study. First, owing to the massive concentrations of wealth and transport demand in India's medium and large cities, it is likely that majority of the BEV uptake over the next two decades will be concentrated in these cities (Das & Parikh, 2004). Second, because of its relatively higher income levels, Delhi's current trip shares by mode and time of day are expected to reflect travel patterns in other medium and large Indian cities in the future as their incomes increase to Delhi's levels (Bose, 1998). Third, growth in electricity demand from non-BEV sources (such as air conditioners) is expected to be similarly explosive in all urban areas (Phadke, Abhyankar, & Shah, 2013). Fourth, the long-run electricity generation mix is likely to be similar in most parts of the country owing to rapid buildout of transmission capacity and regional uniformity in power plant costs by fuel (Abhyankar et al., 2013b).

2.1. Plug-in Electric Vehicle Infrastructure (PEVI) Model

PEVI is an agent-based stochastic model that simulates the driving and charging behavior of individual drivers for each hour of the day in a virtual road network that can be outfitted with public and private charging infrastructure of any type (i.e., Level 1, Level 2, or DC Fast). In PEVI, we include a representation of the NCT of Delhi, split into 53 travel analysis zones and its road network. Chargers of the following types can be placed in any travel analysis zone:

- Level 1: low-power chargers up to 1.5 kW (in Delhi, service voltage is 230 V, so any charger on a circuit with a capacity up to 6.5 amps is considered Level 1)
- Level 2: medium-power chargers up to 20 kW
- DC Fast: direct-current fast chargers ranging from 30–100 kW

Individual BEV drivers are simulated as they conduct their travels and charge their vehicles. Drivers begin a day with a vehicle, an itinerary of trips, and a set of behavioral rules, which include the following:

- Drivers attempt all of their daily trips.
- They include a factor of safety in their range estimations (10%).

[1] In this paper, we use the terms NCT region and Delhi interchangeably.

- They may or may not have homes in the region, but all drivers have access to a charger at home.
- They seek a charger when they need it.
- Sometimes they seek a charger even if they have enough charge to complete their trip owing to "range anxiety" (based on a random process derived from observed use of public chargers in the United States by plug-in hybrid electric vehicle drivers).
- They consider neighboring and en route zones in their list of candidate charging sites, but only if desperate for a charge (within 1 hour of departure without sufficient range).
- They choose the charging option that minimizes their cost, a calculation that places a monetary value on their time (Rupees (Rs) 28/hour based on the average income levels of Delhi).

The itineraries that drivers follow are based on two critical sources of data: 1) results from the most recent travel demand model commissioned by the NCT of Delhi and implemented by RITES Ltd. with projections up to 2021 of travel intensities throughout the Delhi metropolitan area (RITES, 2005), and 2) results from the most recent household travel survey with 45,000 respondents (RITES & MVA Asia, 2008). A stochastic, non-parametric resampling technique is used to blend these two data sources into dozens of unique sets of itineraries, which are used in the context of Monte Carlo simulation to include a suitable amount of variability in the analysis. In addition, data from The EV Project, a large-scale demonstration project in the United States, are used in the development of probability distributions that characterize aspects of driver behavior as well as for model calibration (Ecotality, 2013). See Gopal et al (2014) and Sheppard et al (2016) for more details on the PEVI modeling approach.

2.1.1. Total Vehicle Stock in 2030

We project the future stock of vehicles using a simplified stock turnover model. We first take the current number of registered vehicles in India as reported by the Ministry of Road Transport and Highways (Table 1).

Table 1: Total number of registered vehicles in India (in millions)

	2000	2005	2010	2013
Two-wheelers	34	59	92	133
Cars, Jeeps, and Taxis	6	10	17	25
Buses	0.6	0.9	1.5	1.9
Goods Vehicles	3	4	6	9
Others	5	7	11	15
Total	**49**	**81**	**128**	**182**

Source: (MORTH, 2015)

Unfortunately, the registered vehicle data for later years are not available in the public domain. Note that these cumulative numbers of all registered vehicles do not account for vehicle retirement. According to (Guttikunda & Mohan, 2014), only 70% of these vehicles are actually operating on the road. Therefore, the total active vehicle stock in 2013 is assumed to be about 128 million; this includes about 93 million two-wheelers and 17 million cars. We then project the vehicle sales up to 2030 based on the historical trends. We take the historical vehicle sales data from the Society of Indian Automobile Manufacturers (SIAM) as shown in Table 2.

Table 2: Total vehicle sales in India (in millions)

Category	2000	2005	2010	2015
Passenger Vehicles (Cars)	0.6	1.1	2.0	2.6
Two-wheelers	3.8	6.6	9.4	16.0

Source: (SIAM, 2011, 2016)

It is clear from Table 1 and Table 2 that vehicle sales have been growing rapidly. Between 2000 and 2015, car and two-wheeler sales have more than quadrupled, indicating a compound annual growth rate (CAGR) of 10%. During the same period, the number of registered vehicles quadrupled as well.

For projecting the vehicle stock in the future, we use a simplified vehicle stock turnover model. We assume that car sales will continue to grow at the same rate as observed historically, with sales nearly quadrupling in about 15 years. In the case of two-wheelers, we assume the sales growth rate would slow owing to increased incomes, especially in urban areas; we assume two-wheeler sales will only double between 2015 and 2030. This assumption roughly matches industry forecasts and other studies (Guttikunda & Mohan, 2014). All vehicles (cars and two-wheelers) are assumed to have a life of 15 years. Table 3 shows our projections for vehicle sales and total active vehicle stock up to 2030.

Table 3: Projected total vehicle sales and active vehicle stock (millions)

		2015	2020	2025	2030
Sales	Two-wheelers	16	20	26	32
	Cars	2.6	4.1	6.5	10
Active stock	Two-wheelers	122	204	289	367
	Cars	22	38	59	89

Note: These numbers only represent active vehicles operating on the street. The number of registered vehicles would be higher.

2.1.2. BEV Stock in 2030

We assume that, by 2030, all light duty passenger vehicles (i.e. cars and two-wheelers) sold in India are BEVs. Indian BEV sales in 2015 were very low (about 20,000). We assume a log-linear growth of BEV sales, with the growth rate changing every 5 years between 2015 and 2030. As shown in Table 3, we assume that the total vehicle sales (and stock) remain the same whether consumers choose BEVs or conventional internal combustion engine (ICE) vehicles. Therefore, as BEV sales grow, ICE vehicle sales drop, and by 2030 BEVs account for 100% of vehicle sales in India (Table 4).

Table 4: Projected BEV and ICE vehicle sales (millions) by 2030

	Vehicle Sales (millions)							
	Two-wheelers				Cars			
	2015	2020	2025	2030	2015	2020	2025	2030
ICE	16.0	19.7	20.2	0.0	2.6	3.8	4.1	0.0
BEV	0.0	0.5	5.4	32.3	0.0	0.3	2.4	10.3
Total	16.0	20.2	25.6	32.3	2.6	4.1	6.5	10.3

To achieve the 100% vehicle sales electrification goals, two-wheeler BEV sales must increase from about 2,000 in 2015 to about 32 million in 2030, and BEV car sales must increase from about 20,000 in 2015 to about 10 million in 2030.

Table 5 shows the active BEV and ICE vehicle stocks by 2030. The active vehicle stock at the national level is distributed among all states based on their historical shares. By 2030, BEVs represent about 29% of the total active two-wheeler stock and about 44% of the total active car stock. Full vehicle stock electrification would be expected to take place by mid-2040, when all ICE vehicles purchased before 2030 would likely be retired.

Table 5: Active stock (millions) of BEVs and ICE vehicles up to 2030

	Active Vehicle Stock (millions)							
	Two-wheelers				Cars			
	2015	2020	2025	2030	2015	2020	2025	2030
ICE	121.9	203.5	275.9	262.0	22.2	37.0	51.7	49.9
BEV	0.0	0.7	13.6	105.1	0.0	0.6	7.0	39.0
Total	121.9	204.2	289.5	367.1	22.2	37.7	58.6	88.9

2.1.3. Vehicle Efficiency

Vehicle characteristics (especially efficiencies) could vary widely by vehicle class. For example, a compact sedan's fuel efficiency would be significantly different from a van's. To account for such differences, we split cars into three different classes: subcompact hatchbacks, compact sedans, and vans/multi-use vehicles (MUVs). These classes and the market shares of each are derived from SIAM's all-India vehicle sales data in 2015 (SIAM, 2011, 2016). Two-wheelers are not split into sub-classes, mainly because data are lacking.

For each vehicle category, we take the best-selling ICE vehicle or BEV model in India and use the manufacturer-labeled fuel (gasoline, diesel, electricity) efficiency values for 2015. We assume that vehicle efficiencies will improve between 2015 and 2030. From 2016–2017 onward, all new light-duty (passenger) ICE vehicles sold in India will have to comply with the energy consumption standard (BEE, 2014). The Bureau of Energy Efficiency has already specified a trajectory for improving the fleet average efficiency through 2021–2022. Between 2017 and 2022, the average rate of efficiency improvement is expected to be about 2.8% per year (ICCT, 2014). We assume that, between 2022 and 2030, ICE vehicle efficiency improvement continues at the same rate. Note that this rate is higher than the historical efficiency improvement, which has been about 2.0% per year (ICCT, 2014). Table 6 shows our assumptions for ICE vehicle fuel economy values in 2015 and 2030.

Table 6: ICE vehicle efficiency (km/L) in 2015 and 2030

	Model	Fuel	ICE Fuel Economy (km/L)	
			2015	2030
Two-wheeler	Honda Activa 3G	Gasoline	60.0	86.3
Subcompact Hatchback	Maruti WagonR VXI	Gasoline	20.5	29.5
Compact Sedan	Maruti Dzire AT	Gasoline	18.5	26.6
Van/MUV	Toyota Innova	Diesel	11.0	15.8

In the case of BEVs, two-wheelers and subcompact hatchbacks are somewhat widely available and in use already. Compact sedan and MUV BEVs, such as the Mahindra Verito (compact sedan) and Mahindra eSupro (minivan), have much lower availability and sales. Moreover, based on manufacturer specifications, these larger vehicles tend to use the same battery pack and have similar ranges as their subcompact hatchback counterparts. Therefore, we do not use manufacturer-labeled efficiencies for compact sedans and MUVs. We use a mixed approach instead. First, we take the ratio of the compact sedan and MUV efficiencies to subcompact hatchback efficiency from a study assessing the potential for reducing GHG emissions from U.S. light-duty vehicles between 2015 and 2050 (NRC, 2013). We then multiply the manufacturer-specified subcompact hatchback efficiency in India by this ratio to estimate the compact sedan and MUV efficiencies in India.

We are not aware of any analysis that projects BEV efficiency improvement in India in the medium to long term. Therefore, we also take the rate of improvement up to 2030 from NRC

(2013). Given the globalized supply chain of automobile and battery manufacturing, we believe such improvement rates would not be very different in India. Table 7 shows our assumptions for BEV efficiencies in 2015 and 2030.

Table 7: BEV efficiency (Wh/km) in 2015 and 2030

Vehicle Type	Model	BEV Efficiency (Wh/km)	
		2015	2030
Two-wheeler	Hero Electric Zion	32	23
Subcompact Hatchback	Mahindra E2O Plus	114	70
Compact Sedan	-	138	84
Van/MUV	-	185	113

To assess the robustness of our findings to the BEV efficiency assumptions, we conduct a sensitivity analysis on vehicle fuel efficiencies in 2030 (see Section 3.2).

2.1.4. Vehicle Kilometers Traveled

Based on the travel demand survey in the NCT in 2008, the average annual vehicle kilometers traveled (VKTs) by two-wheelers are 2,942 km/yr and by cars are 2,893 km/yr (RITES & MVA Asia, 2008). However, several other studies have shown significantly higher VKTs in Delhi, ranging from about 12,000 to 14,000 km/yr. See for example (Goel, Guttikunda, Mohan, & Tiwari, 2015; Ravinder & Eramapalli, 2014; Verma et al., 2015). We use the VKT estimate by Goel et al. (2015)—12,200 km/yr for cars and 12,800 km/yr for two-wheelers—which is based on a survey of more than 3,700 drivers at fueling stations. Verma et al. (2015) show that VKTs in other cities are significantly lower than those in Delhi. For example, daily car kilometers per person in Bangalore are less than half of those in Delhi (Verma et al., 2015).

Unfortunately, we do not have time-series data on VKTs or travel demand. Therefore, we use an indirect approach to project them to 2030. Between 2015 and 2030, India's average per-capita GDP is expected to double (in real terms at Purchasing Power Parity (PPP)), from $4,000 to $9,000 (OECD, 2013). Delhi's per-capita GDP in 2015 was estimated to be $8,700 (PPP in 2005 constant U.S. dollars), which is almost the same as 2030 projections for India as a whole (Berube, Trujillo, Ran, & Parilla, 2015) (Table 8). Thus, we assume that the 2030 travel demand (travel behavior as well as VKTs) in all other regions in India, will be similar to Delhi's 2015 travel demand

Table 8 shows our assumptions for Indian per-capita GDP (in constant 2005 dollars) and average VKTs in 2015 and 2030. By 2030, average VKTs in India would still be lower than current VKTs in other industrialized and emerging economies such as the United States (19,801), Germany (12,446), and China (14,125) (DOT, 2010).

Table 8: GDP per capita and VKTs in 2015 and 2030

		2015	2030
Average VKTs (km/yr)	Two-wheelers	12,800 (Delhi only)	12,800 (all-India)
	Cars	12,200 (Delhi only)	12,200 (all-India)
GDP per Capita (PPP constant 2005 U.S. $) *		4,000 (all-India)	9,000 (all-India)
GDP per Capita (PPP constant 2005 U.S. $) **		8,700 (Delhi only)	

* Source: (OECD, 2013)

** Estimated using the 2013–2014 number from (Berube et al., 2015). Deflators taken from (OEA, 2009, 2015).

2.1.5. Vehicle Costs

For ICE vehicles, we start with 2015 manufacturer suggested retail prices for capital costs. As the efficiencies of ICE vehicles improve significantly between 2015 and 2030, their capital costs are expected to increase slightly. Because no study forecasts vehicle costs in India, we apply the cost trend between 2015 and 2030 from NRC (2013) to current ICE vehicles costs in India; the relative increase in capital cost between 2015 and 2030 is much smaller than the efficiency improvement. For BEVs, we use manufacturer-labeled prices for two-wheelers and subcompact hatchbacks. For compact sedans and MUVs, we use the same approach as we use for BEV efficiency: we estimate the compact and MUV prices using the ratios of their prices to the prices of subcompact hatchbacks from NRC (2013). For projecting the BEV costs in India up to 2030, we apply the BEV cost trends from NRC (2013) to the 2015 costs. Table 9 shows our assumptions for vehicle capital costs in 2015 and 2030.

Table 9: Assumptions for vehicle capital costs in 2015 and 2030 (Rs)

	2015		2030	
	ICE*	BEV	ICE	BEV
Subcompact Hatchback	441,050	703,905*	473,912	582,769
Compact Sedan	709,598	1,014,725	762,590	840,114
MUV	1,104,511	1,579,451	1,186,874	1,307,629
Two-wheeler	46,986	46,150*	53,725	40,954

* Note: Manufacturer-labeled prices (ex-showroom in Delhi). BEV (Mahindra E2O plus) price is exclusive of the Government of India’s FAME subsidy.

Declining BEV capital costs are mainly due to expected advancements in battery technology (improved energy density and economies of scale in production). Between 2015 and 2030, the incremental capital cost of BEVs over ICE vehicles drops by more than 60%–70%.

We assume annual maintenance and spare parts costs equivalent to 5% of capital costs. The fuel price for ICE vehicles is from government-approved prices in 2015 of Rs 60/L for gasoline and Rs 50/L for diesel, which we believe are conservative. The marginal electricity price is assumed to be Rs 9/kWh based on actual marginal electricity tariffs for residential customers in Mumbai and Delhi in 2015. Fuel price and electricity price are held constant through 2030.

2.2. Power System Modeling Using PLEXOS

We model the Indian electricity grid using five nodes, one node for every region: north, east, west, south, and northeast. In PLEXOS, we run two modules: capacity expansion and economic dispatch. The capacity-expansion module takes 2030 as the terminal year; i.e., the model is not assumed to have foresight beyond 2030. The output of the capacity-expansion module (total number of units in each region including the modeled additions until 2030) is used by the economic dispatch model. We run the economic dispatch model in two stages. The first stage simulates the day-ahead scheduling and market. In the day-ahead mode, the model takes the day-ahead RE forecasts and expected maintenance outages and makes the unit-commitment decisions for thermal power plants. These RE forecasts are revised up to 3 hours in advance to reduce the forecast errors significantly and potentially revise the unit-commitment schedule, if necessary and feasible. The second stage simulates the hourly real-time grid operation and power plant dispatch. In the real-time mode, the model takes the unit-commitment decisions from the day-ahead mode (revised up to 3 hours ahead) and does the economic dispatch considering the actual (i.e., forecasts of the 2030 real-time) RE generation and load (BEV and non-BEV). The unit-commitment and dispatch decisions are made to minimize the total system cost (production as well as startup and shutdown costs) subject to operational constraints such as maximum ramping rates, minimum stable generation levels, minimum up and down times, and so forth. Note that these are energy-only simulations and do not include ancillary services such as reserves.

2.2.1. Electricity Generation Capacity

We create the following two scenarios for the installed electricity generation capacity in 2030:

(a) ***Business as Usual (BAU)***: This baseline scenario uses the generation capacity additions for conventional technologies as projected in the Central Electricity Authority's (CEA's) NEP 2016 (CEA, 2016b). For RE technologies, we take the capacity-expansion projections from Government of India's 12^{th} 5-year plan (Planning Commission, 2012). Note that the NEP has targets up to 2027, and the 12^{th} plan has targets up to 2022; we do a linear extrapolation of these targets to 2030.

(b) ***NDC Compliant***: This scenario models India's NDC in the Paris Climate Agreement to increase the total installed capacity of solar photovoltaic (Solar PV) projects to 100 GW and wind projects to 60 GW by 2022; we linearly extrapolate these targets to 2030. The RE capacities are similar to those projected in the NEP, which assumes compliance with India's NDC commitment to RE. We hold the nuclear and hydro capacities the same as in the BAU scenario owing to a range of non-economic constraints driving their construction, and we let PLEXOS's capacity-expansion module optimize coal and gas capacity additions in 2030.

Table 10 summarizes our scenarios and shows 2015 actual values.

Table 10: Assumptions for total (all-India) installed generation capacity by 2030 in GW

	2015 (Actual)*	2030 BAU	2030 NDC Compliant
Coal	165	420	Optimized by PLEXOS
Gas	24	42	Optimized by PLEXOS
Diesel	1.1	1.1	1.1
Nuclear	5.8	18	18
Hydro	41	79	79
Wind	22	58	110
Solar PV (including distributed solar)	3.1	39	180
Other RE	8.0	20	20
Total	**265**	**677**	**#N/A**

Note: Totals may not match individual values owing to rounding.
* Source: (CEA, 2015a)

2.2.2. Wind and PV Generation Profiles

We forecast the hourly profiles of wind energy generation using historical generation data for 2010 through 2013 from the states of Tamil Nadu, Karnataka, Maharashtra, and Gujarat. For estimating the hourly Solar PV generation profile, we use 100 sites spread over all five regions with the best solar resource (measured in direct normal irradiance and global horizontal irradiance, kWh/m^2) using the national solar energy dataset for India developed by the National Renewable Energy Laboratory (NREL, 2013). Simulated hourly PV output profiles of the sites in each region are averaged to arrive at the regional Solar PV generation profile. See Appendix 1 for details.

2.2.3. Non-BEV Electricity Demand

We simulate the hourly demand curve for each region based on the historical hourly demand patterns in the country, growing urbanization, and the projected load growth based on the CEA's NEP 2016 (CEA, 2016b). One of the key problems in projecting the future demand is accounting for load curtailment (which was as high as 6% by energy in 2013 but dropped to less than 1% in 2016). To address that, we use a mixed approach. We use the current restricted load data for each region to assess the seasonal load pattern in a region, and we use hourly load data for key load centers that do not experience load shedding (such as Delhi, Chandigarh, Gujarat, Mumbai, and Pondicherry) and load centers that have load-shedding data available (such as Maharashtra and Tamil Nadu) to assess the diurnal demand pattern. For estimating the 2030 demand, we apply the demand growth rates from CEA's NEP. Note that NEP projects the load only until 2027, and we extrapolate it to 2030. To account for growing urbanization, load shapes of the urban load centers (such as Delhi, Mumbai, and Pondicherry) are given an additional 20% weight relative to the state-level load curves in each region. This makes the 2030 load curve peakier than the current (2015/2016) one. Finally, the regional load curve is uniformly adjusted so that the peak demand and total energy demand in 2030 match those estimated using NEP growth rates. Demand forecasting and load-shape assessment require future research using a combination of bottom-up and top-down approaches. Table 11 shows the projected energy demand, peak demand, and load factor[2] for 2030 in each region.

Table 11: Projected non-BEV energy demands, peak demands, and load factors for 2030

Region	Energy Demand (non-BEV) (TWh/yr)	Peak Demand (non-BEV) (GW)	Load Factor (%)
Northern	776	116	77%
Western	702	115	70%
Southern	686	115	68%
Eastern	326	51	73%
Northeastern	32	6	61%
All-India	**2,522**	**402**	**72%**

2.2.4. Generator Costs and Operational Parameters

Generator operational parameters such as unit size, heat rates, ramp rates, and minimum stable level of the power plants are estimated using historical plant-level hourly dispatch, outage and other performance data, regulatory orders on heat rates and costs, other relevant literature, and conversations with system operators in India about actual practices. Our assumptions for operational parameters are listed in Appendix 1 and Appendix 2. Capital costs and fixed operations and maintenance (O&M) costs for renewable technologies are from India's Central Electricity Regulatory Commission's (CERC) tariff norms for 2014–2015. For coal-based power projects, we use CERC's interim order (2012) on benchmarking the capital costs of thermal

[2] Load factor is the ratio of average load to peak load and shows the spread of the load curve. As load factor value gets smaller, it indicates that the load curve gets peakier.

projects (CERC, 2012). For gas, diesel, and hydro projects, we use industry norms per our previous report (Abhyankar et al., 2013a). Capital and O&M costs of the nuclear projects are from (Ramana, D'Sa, & Reddy, 2005). Given that most of the conventional technologies have already matured, their capital costs are not assumed to change through 2030 in real terms. For PV, we use the capital cost trajectory projected in the Global PV Market Outlook 2015 (BNEF, 2015). For wind, given the historical trends, capital cost is assumed to remain the same in real terms (Wiser & Bolinger, 2015). For details, see Appendix 1.

2.2.5. Fuel Prices and Availability

We take 2015 fuel prices and use historical trends to project fuel prices in 2030. Domestic coal availability for the power sector is from the Ministry of Coal's projections in the 12th 5-year plan up to 2017; the same trend is projected up to 2030. We assume domestic gas availability for the power sector in the future remains the same as the current quantity. No quantity restrictions are assumed on imported fuels. For details, see Appendix 1.

2.2.6. Power Plant Emission Factors

Table 12 shows our assumptions for CO_2 emission factors from fossil fuel power plants. They are from CEA's database of CO_2 emissions from the power sector in India (CEA, 2016a).

Table 12: CO_2 emission factors from power plants

Fuel	Unit Size (MW)	CO_2 Emissions kg/kWh
Coal	67.5	1.19
Coal	120	1.05
Coal	200–250	1.05
Coal	300	0.99
Coal	500 (Type 2)	0.97
Coal	600	0.97
Coal	660 (Type 2)	0.87
Coal	800	0.85
Gas (Open Cycle)	All sizes	0.66
Gas (Combined Cycle)	< 50	0.42
Gas (Combined Cycle)	50–100	0.41
Gas (Combined Cycle)	> 100	0.42
Diesel	All sizes	0.63

Source: (CEA, 2016a)

2.2.7. Transmission

India is already planning significant new investments in transmission expansion. Therefore, we assume no constraints on transmission by 2030.

2.2.8. Smart Charging

BEV charging load could be shifted to a different time of day to reduce total system costs. Such load shifting is called smart charging. We allow such shifting of the charging events for non-essential charging demand in each hour. Smart charging is subject to the daily energy balance constraint; that is, the daily BEV charging load in case of smart charging should be exactly the same as in the fixed charging case. In PLEXOS, we implement the smart-charging system by modeling the charger/vehicle system as flexible storage; the non-essential part of this hypothetical storage (in the form of car batteries) could be charged any time during the day so that the system cost is minimized. One implicit assumption is that daily BEV itineraries are decided at the start of each day and are not altered during the day. We intend to relax this constraint in our future work.

2.3. Estimating Per-Kilometer CO_2 Emissions

Per-kilometer CO_2 emissions from ICE vehicles are estimated as follows:

$$\frac{g\ CO_2}{km}_{ICE} = Fuel\ consumption\ (gasoline\ or\ diesel)\ per\ km\ \ x\ Emission\ factor$$

Fuel consumption for ICE vehicles is from Table 6. Emission factor (8.78 kg CO_2 per gallon for gasoline and 10.21 kg CO_2 per gallon for diesel) is from (US EPA, 2015).

For BEVs, per-kilometer CO_2 emissions are calculated as follows:

$$\frac{g\ CO_2}{km}_{BEVs} = Electricity\ consumption\ per\ km\ x\ Temporally\ explicit\ grid\ emission\ factor$$

The BEV electricity consumption rates are in Table 7. The temporally explicit grid emissions factor for BEV charging load is estimated by averaging the hourly grid emission factor for the national grid weighted by the hourly BEV charging load. The hourly grid emission factors are from the hourly power plant dispatch simulations in PLEXOS.

2.4. Estimating Crude Oil Consumption

Total annual crude oil consumption from ICE vehicles is estimated as follows:

$$Crude\ oil\ consumption/yr = Fuel\ consumption\ per\ km\ \ x\ \ VKTs/yr\ \ x\ \ Crude\ oil\ conversion\ factor$$

Where fuel consumption per km is from Table 6 and VKTs per year are from Table 8. Based on U.S. Energy Information Administration assessments, the crude oil conversion factor is assumed to be 2 for gasoline and 3 for diesel (EIA, 2016).

3. Results

In this section, we present the key results of our analysis.

3.1. BEV Owners Can Gain Significantly

As shown in Table 9, the incremental capital cost of BEVs over ICE vehicles drops by over 60%–70% between 2015 and 2030. For example, the incremental capital cost of subcompact hatchbacks is expected to drop from nearly Rs 250,000 in 2015 to Rs 100,000 in 2030. Figure 6 compares the annualized incremental cost of BEVs (i.e., annualized incremental capital cost and total annual electricity cost) with the total annual fuel cost of ICE vehicles for subcompact hatchbacks. The annualized capital cost is estimated using a preferential interest rate of 6%.

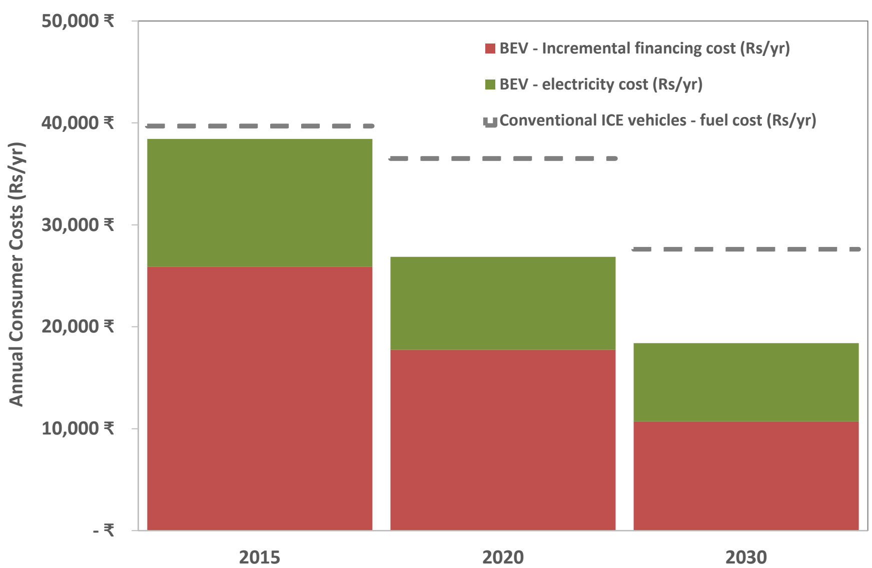


Figure 6: Annualized incremental cost of BEVs and annual fuel cost of ICE vehicles for subcompact hatchbacks

Between 2015 and 2030, as the ICE vehicle efficiency increases, the annual fuel cost of ICE vehicles drops by over 30%. Despite this cost reduction, the total incremental cost of BEVs is lower than the annual fuel cost of ICE vehicles for all years. The difference between the ICE fuel cost and the total incremental cost of BEVs is the net BEV owner's benefit. By 2030, the net BEV owner's benefit is more than Rs 9,200/yr; the difference in only the annual fuel costs of ICE vehicles and BEVs is about Rs 20,000/yr, indicating a simple payback period of about 5 years by 2030.[3] Owing to the deep reduction in BEV capital cost, the net owner's benefit increases

[3] Simple payback period is estimated by dividing the annual savings in operating costs by the incremental capital cost.

significantly between 2015 and 2030. The share of incremental capital cost in the total incremental BEV cost drops from 75% in 2015 to about 50% in 2030. Therefore, the owner's benefit is highly sensitive to the interest rate assumption in the initial years; BEV bulk procurement and incentive programs with preferential financing are crucial for early adoption. To demonstrate this, Figure 7 compares the total incremental cost of BEVs (incremental financing cost and electricity cost) with the annual fuel cost of ICE vehicles in the subcompact hatchback category for a range of interest rates (6%–12%).

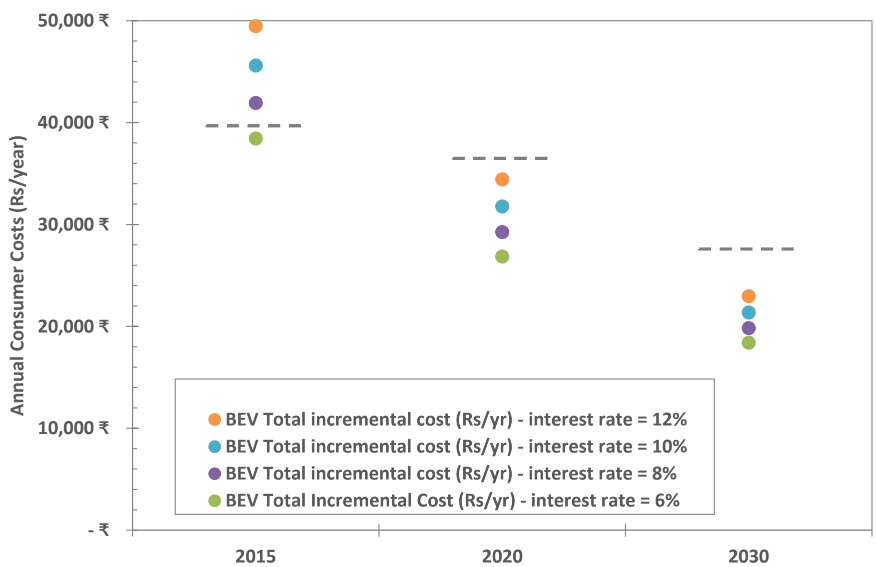


Figure 7: Sensitivity of BEV total incremental cost to assumed interest rate

In 2015, if the interest rate is higher than 6%–7%, the BEV owner's net benefit is negative (i.e., annual BEV costs are higher than ICE vehicle costs). However, by 2020 and 2030, BEV costs drop significantly, and BEVs are cost-effective for owners even at interest rates up to 12%.

Another important determinant of BEV cost-effectiveness is distance traveled. Since our estimation of future VKTs is based on several assumptions, we analyze the sensitivity of our results to VKTs. Figure 8 shows the total incremental cost of BEVs (incremental financing cost and electricity cost) and the annual fuel cost of ICE vehicles in 2030 for a range of VKT assumptions for subcompact hatchbacks: +/- 50% of our base assumption of 12,200 km/yr.

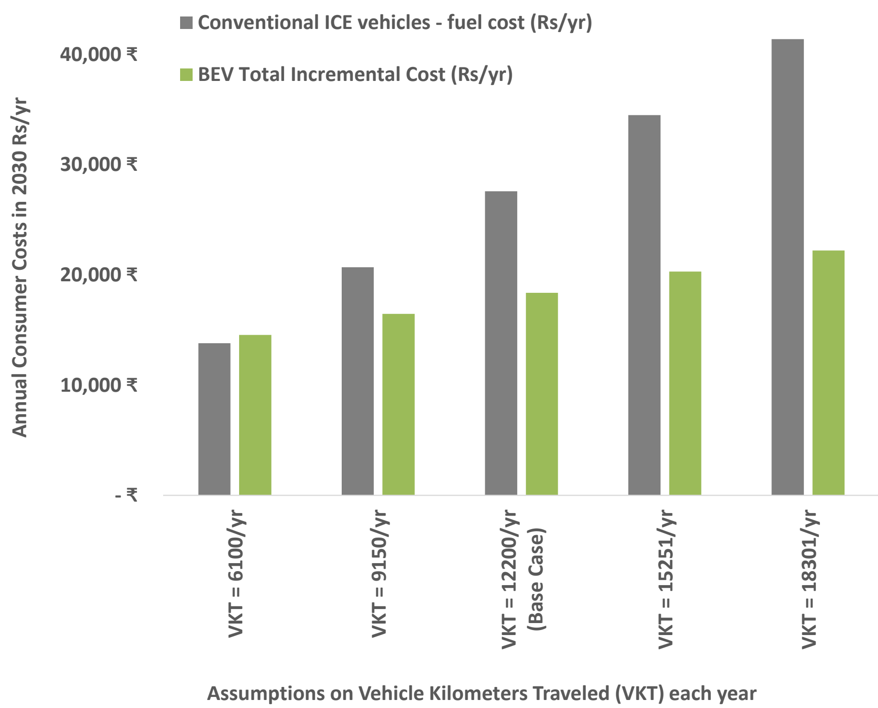


Figure 8: Sensitivity of consumer costs in 2030 to VKTs for subcompact hatchback BEVs and ICE vehicles

As VKTs increase, BEVs become more financially attractive. For high VKTs, the net owner's benefit is as high as Rs 20,000/yr in 2030. Conversely, for low VKTs (less than around 6,500 km/yr), BEVs may not be fully cost-effective. Given the rise of shared mobility services in India (like Uber and Ola), this has a major bearing on BEV adoption policies and programs. Since taxis (including shared-service vehicles) have much higher VKTs than other passenger vehicles, they could be considered among the first candidates for BEV adoption. Moreover, they could be converted as a fleet, thereby significantly reducing transaction as well as program administration costs. However, access to public charging infrastructure would be crucial for such programs.

3.2. Additional Load due to BEV Charging Is Minor

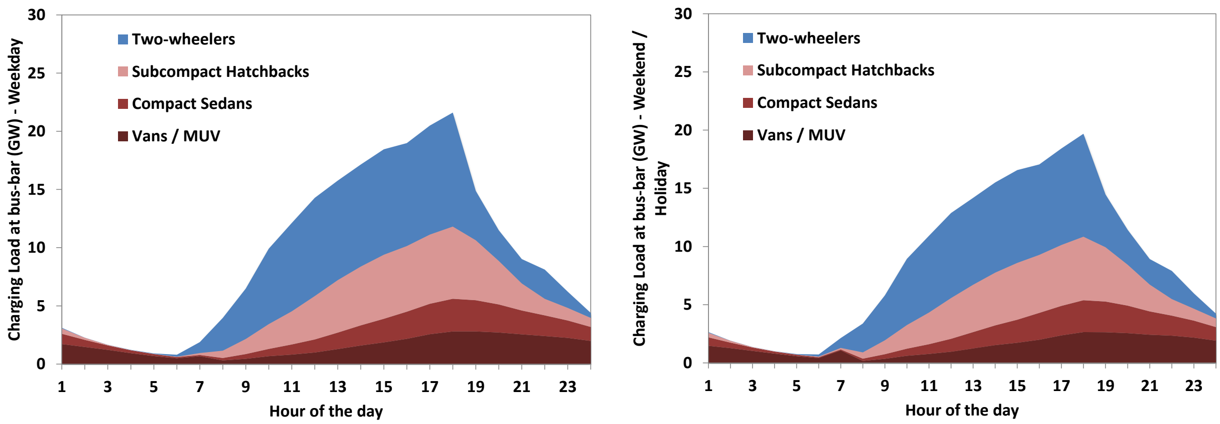
As shown in Table 13, despite aggressive vehicle electrification, the additional load added due to BEV charging in 2030 is only 3.3% of India's total electricity load (Table 13). This is mainly because of the following three reasons: (a) in most urban areas of India, the rapid increase in electricity demand from numerous other end uses (particularly air conditioners) will be very large over the next 15–20 years, (b) vehicle penetration by 2030 is dominated by two-wheelers that require much less energy than cars, and (c) the overall vehicle penetration is expected to be significantly lower than the penetration in other industrialized or emerging economies.

Table 13: Annual energy consumption at bus-bar due to non-BEV electric load and BEV charging in India in 2030 (TWh/year)

Non-BEV Electric load	**2,522**
BEV Charging Load	
Two-wheelers	36
Cars	46
Aggregate BEV Charging Load	**82**

Note: Transmission and distribution loss is assumed to be 15%.

Figure 9 shows the average hourly BEV charging load in 2030 during a typical weekday and a weekend/holiday. The total peak BEV charging load is 23 GW, which is about 6% of the total peak load by 2030 (402 GW). Figure 10 shows the aggregate BEV charging load and average hourly load curve for the non-BEV load in May 2030.



(a) Typical weekday (b) Typical Weekend/Holiday

Figure 9. Average hourly BEV charging load (100% electrification of vehicle sales)

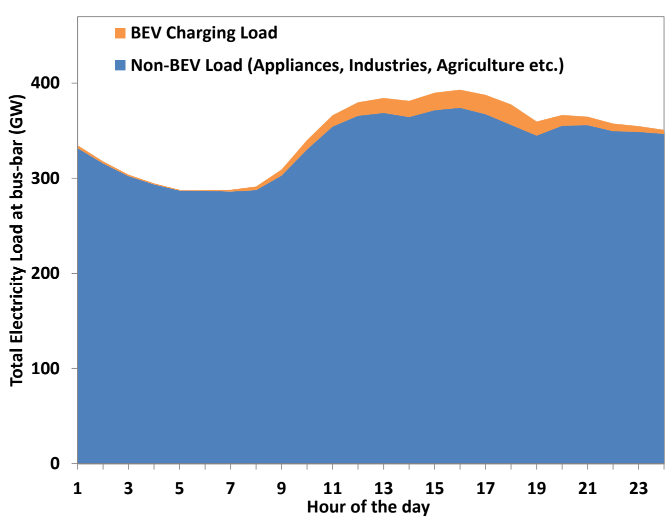


Figure 10: All-India average daily load curve and BEV charging load in May 2030

The two-wheeler BEV charging load curve is shaped very differently from the results we see from BEV car charging in the United States (Ecotality, 2013). This is due to two major factors. First, two-wheelers are used for a wide variety of purposes and not necessarily the traditional commute. Hence, large numbers of two-wheeler trips begin and end throughout the daytime hours. Since these vehicles are usually plugged in at the end of each trip, we see high charging demand from 10 AM to 6 PM. Second, two-wheelers have a low battery capacity (1.5–2 kWh) and hence frequently complete charging within an hour, even at Level 1 rates. Therefore, we see a substantial drop in demand from 6 to 7 PM as many two-wheeler trips end in those hours.

In contrast, the daily BEV charging demands from cars and vans/MUVs follow a similar pattern to that seen in the United States, mostly associated with commuting (Ecotality, 2013). Most drivers plug in their vehicle when they return home in the evening, while a significant share also charges at public locations during the day. Since most of the chargers in use are Level 1, vehicles with greater battery capacity draw power during more hours of the day—subcompacts can be fully charged from empty in less than 5 hours using a Level 1 charger, while it takes a van 13 hours to fill up from empty using the same charger.

The BEV charging load on a weekend/holiday is lower than on a weekday, but the shape is not significantly different. This is primarily because most BEVs are two-wheelers, which may not be used for the traditional commute. Overall, the charging demand from two-wheelers in each daytime hour constitutes the dominant share of all BEV demand, mainly because of their large number. Moreover, the hourly charging profile has a strong correlation with the wind and PV generation profiles shown in Appendix 1; this makes the temporally explicit grid emission factors for BEV charging load lower than the factors for non-BEV electric load.

Total BEV energy consumption is affected by almost every key assumption/parameter, such as BEV stock (i.e., vehicle sales growth), VKTs, and BEV efficiency. However, because the non-BEV load and its growth is significantly larger than BEV charging load, the grid impact of changing these parameters is expected to be minor. Table 14 shows the impact on BEV charging load and peak demand of changing these parameters by +/-25%.

Table 14: Sensitivity of BEV energy consumption and peak demand to key parameters

	Base Case	Sensitivity on VKTs		Sensitivity on BEV Efficiency		Sensitivity on Vehicles Sales Growth	
Vehicles Sales Growth % p.a. (weighted average CAGR 2015–2030)	5.7%	5.7%		5.7%		4.3%	7.1%
BEV Efficiency (Wh/km) (weighted average)	43	43		32	54	43	
VKTs (km/yr) (weighted average)	12,641	9,481	15,802	12,641		12,641	

BEV charging energy consumption at bus-bar in 2030 (TWh/yr)	82	62	103	62	103	67	100
BEV Charging Peak Load in 2030 (GW)	23	19	26	39	39	19	28

The overall range for BEV energy consumption in 2030 is 62–103 TWh/yr (2.4%–4% of the non-BEV energy load) and for peak load is 19–39 GW (4.6%–9.7% of the non-BEV peak load). If passenger vehicle sales growth slows (potentially due to increased adoption of shared mobility services like Uber or Ola), the total BEV energy requirement will decline, although that may be accompanied by an increase in VKTs. If vehicle sales grow faster than in our base case, total energy consumption and peak load will increase, but that increase is minor relative to the non-BEV electricity load. Similarly, if VKT and BEV efficiency assumptions are changed, the energy consumption results change proportionately, but those changes are minor relative to the non-BEV load. Note that peak charging load does not vary proportionately with the change in VKTs.

3.3.BEV Charging Load Can Earn Additional Revenue for Utilities

Although the additional load due to BEV charging is minor, it could still provide a valuable additional revenue source for the financially distressed distribution utilities, as shown in Figure 11. Assuming a marginal electricity tariff of Rs 9/kWh, by 2030, BEV charging load could generate about Rs 70,000 Cr/yr ($10 billion/yr) of additional revenue for utilities.[4]

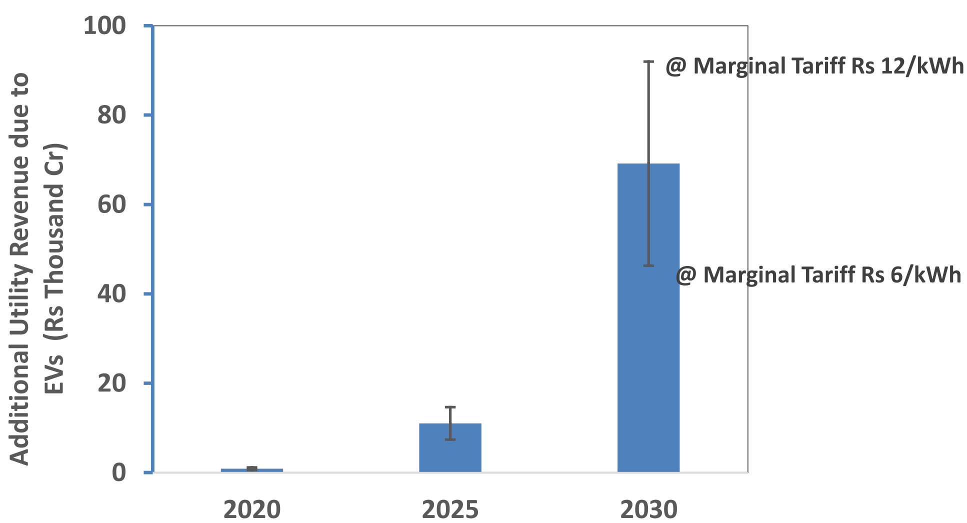


Figure 11: Additional utility revenue due to BEV charging load (Rs thousand Crore)

In 2014, the total utility financial deficit was Rs 62,000 Cr/yr, and the total government subsidy support to utilities was about Rs 36,000 Cr/yr (PFC, 2016). Also in 2014, total revenue from the

[4] Cr stands for Crore. 1 Crore = 10 million (10^7).

commercial sector was Rs 42,000 Cr/yr (PFC, 2016). Between 2015 and 2030, commercial-sector energy consumption is expected to nearly double; assuming the average commercial tariff remains the same in real terms, commercial-sector revenue would also double (to Rs 84,000 Cr) in real terms by 2030. In short, by 2030, the additional revenue due to BEV charging load would be comparable to that of the commercial sector.

The additional utility revenue is linearly proportional to the assumed marginal tariff. Our assumed marginal tariff is based on the residential tariffs in Mumbai and Delhi. However, in other regions, marginal tariffs could be different. Figure 11 also shows the additional revenue in 2030 with marginal tariffs of Rs 6/kWh and Rs 12/kWh, which change the revenue to Rs 46,000 Cr ($7 billion) and Rs 92,000 Cr ($14 billion), respectively. Even with a lower marginal tariff, the additional revenue could help reduce the utility financial deficit.

We assume that BEV owners will have access to public charging facilities, which could be a major challenge given the aggressive electrification levels. Deployment of such charging infrastructure could be financed using the additional revenue from BEV charging. Also, it is likely that BEV adoption—especially in the initial years—would be limited to a few major urban centers, resulting in a few hotspot regions. Although the incremental BEV charging load is minor at the national level, its impacts on the local distribution network, especially in potential hotspot regions, could be significant. The problem may worsen (or subside, depending on whether BEVs have smart charging) if the BEV hotspots coincide with PV hotspots. Analyzing such local distribution system impacts is important, and it is part of our future work. For additional discussion of such local effects, see (Waraich et al., 2013; Waraich, Georges, Galus, & Axhausen, 2014).

3.4. BEVs Can Reduce CO_2 Emissions Significantly

Emissions of CO_2 due to BEVs depend largely on the grid emission factors and therefore on the grid's generation mix. Table 15 shows the results of the PLEXOS simulation for installed capacity and electricity generation (all-India) by technology.

Table 15: Installed capacity and electricity generation by technology

	2015 Actual*		2030 BAU		2030 NDC Compliant	
	Installed Capacity (GW)	Electricity Generation (TWh/yr)	Installed Capacity (GW)	Electricity Generation (TWh/yr)	Installed Capacity (GW)	Electricity Generation (TWh/yr)
Coal	165	836	420	1,919	361	1,559
Gas	24	40	42	91	42	91
Diesel	1.1	1.4	1	0	1	0
Nuclear	5.8	36	18	134	18	117

Hydro	41	129	79	234	79	234
Wind	22	40**	58	129	110	274
Solar PV (including distributed solar)	3.1	5**	39	68	180	300
Other RE	8	21**	20	29	20	29
Total	***270***	***1,108***	***677***	***2,604***	***811***	***2,604***
Share of non-fossil sources	*30%*	*21%*	*32%*	*23%*	*50%*	*37%*

* Source: (CEA, 2015a)

** Approximate numbers as CEA reports only total RE generation.

By 2030, the additional PV and wind capacity in the NDC Compliant scenario relative to the BAU scenario is 193 GW. This results in avoiding investment in about 60 GW of coal power plants.

Table 16 shows the temporally explicit (hourly weighted average) grid emission factors in 2030 for the non-BEV electric load as well as the BEV charging load. The grid emission factors are presented for the two scenarios of generation capacity described in Section 2.2.1.

Table 16: All-India average grid emission factor and temporally explicit grid emission factors for BEV charging load —2015 actuals and 2030 projected (kg/MWh)

	2015 Actual*	2030 BAU	2030 NDC Compliant
All-India Average Grid Emission Factor	**820**	**709**	**610**
BEV Charging Load			
MUVs/Vans	N/A	713	621
Compact Sedans	N/A	707	606
Subcompact Hatchbacks	N/A	699	579
Two-wheelers	N/A	696	567

* Source: (CEA, 2016a)

Note that the grid emission factors are different for each BEV type, because their charging load profiles are different.

Two observations emerge from the table. First, even under the BAU scenario, significant decarbonization of the Indian grid is expected. This is mainly due to renewable capacity expansion already planned in the NEP and significant expansion of hydro capacity. Moreover, most of the new coal capacity in India is increasingly more efficient via use of supercritical or ultra-supercritical technologies. In fact, from 2017 onward, the government has mandated that all new coal capacity be only supercritical or ultra-supercritical. Second, the temporally explicit emission factors for BEV charging load (two-wheelers in particular) are generally lower than the average grid emission factors, with the exception of vans. This is mainly because most BEV charging occurs during daytime hours (Figure 9); the grid emission factors during daytime are significantly lower, because both wind and solar energy are available to the grid. MUVs/Vans, however, take much longer to charge owing to larger battery sizes, and thus their charging extends into the early morning hours with limited generation from low-carbon sources.

Using these grid emission factors and equations described in Section 2.3, Figure 12 shows that BEVs have significantly lower per-kilometer CO_2 emissions than ICE vehicles. In the NDC Compliant scenario, BEVs reduce emissions by over 40%–50% for cars (vans, compact sedans, and subcompact hatchbacks) and over 50% for two-wheelers. Even if we assume that none of the decarbonization measures in the BAU plan materialize and the grid in 2030 remains as coal heavy as it was in 2015, BEVs still reduce per-kilometer CO_2 emissions by 20%–30% for cars and about 30% for two-wheelers.

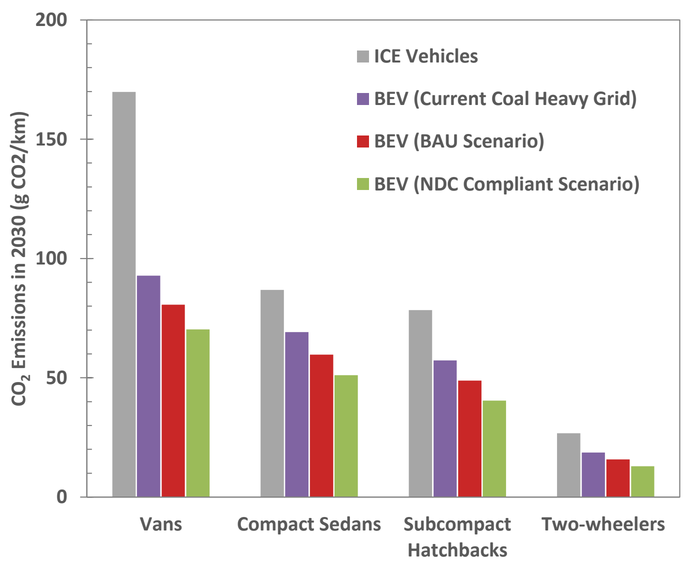


Figure 12: Per-kilometer CO_2 emissions from ICE vehicles and BEVs in 2030

Figure 13 shows total CO_2 emissions by passenger vehicles (cars and two-wheelers) in India up to 2050 if: (a) all passenger vehicles are ICE based, and (b) all vehicle sales beyond 2030 are BEVs. If the NDC Compliant efforts of grid decarbonization continue beyond 2030, passenger transport electrification alone can lower GHG emissions by about 600 million tons/yr by 2050 (about 8% of total GHG emissions by 2050).[5] However, if the clean power targets become more ambitious in the future, even more emissions reductions are possible from the transport sector.

[5] India's total GHG emissions by 2050 are expected to be about 8 billion tons/yr (Gambhir, Napp, Emmott, & Anandarajah, 2014).

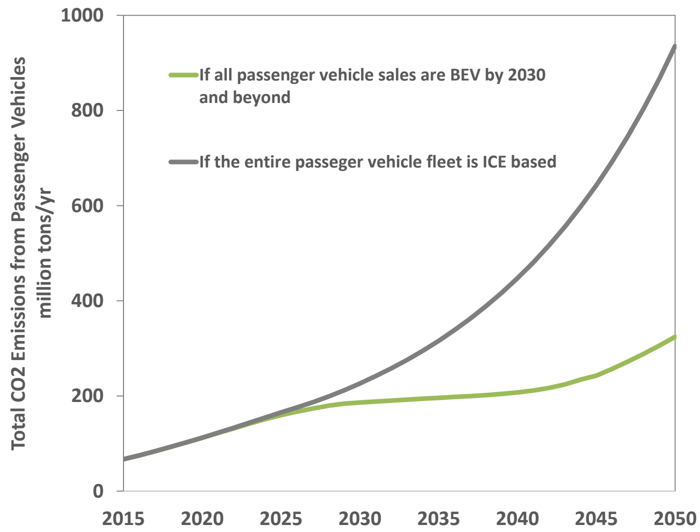


Figure 13: Total CO_2 emissions from passenger vehicles in India (million tons/yr)

3.5. BEVs Can Avoid Crude Oil Imports

By 2030, BEVs can reduce total crude oil consumption by 360 million barrels/yr (15% of total crude oil consumption by 2030).[6] It is projected that more than 80% of the crude oil consumed in India by 2030 will be imported, implying that the entire reduction in crude oil consumption can potentially avoid oil imports (Planning Commission, 2014). Assuming a conservative crude oil price of $40/barrel, BEVs could reduce oil imports by $7 billion/yr by 2030 (about Rs 50,000 Cr/year).

Figure 14 shows total crude oil consumption by the passenger vehicle fleet (two-wheelers and cars) up to 2050, assuming vehicle sales growth continues at the historical rate beyond 2030 as well. If all vehicle sales by 2030 and beyond are BEVs, all ICE vehicles purchased before 2030 retire by the mid-2040s, and total crude oil consumption by the passenger vehicle fleet becomes zero. By 2050, total avoided crude oil consumption would be as high as 2,695 million barrels/yr (about 60% of total crude oil consumption in 2050), and reduced oil import expenses would be $100 billion/yr (Rs 700,000 Cr/yr).[7]

[6] In 2015, India's total crude oil consumption was 1,322 million barrels/yr. It is expected to increase to 2,246 million barrels/yr by 2030 and to 3,199 million barrels/yr by 2040 (IEA, 2015; Karali et al., 2017).

[7] Based on IEA (2015) and Karali et al. (2017), we project that total crude oil consumption in India would be 5,556 million barrels/yr by 2050.

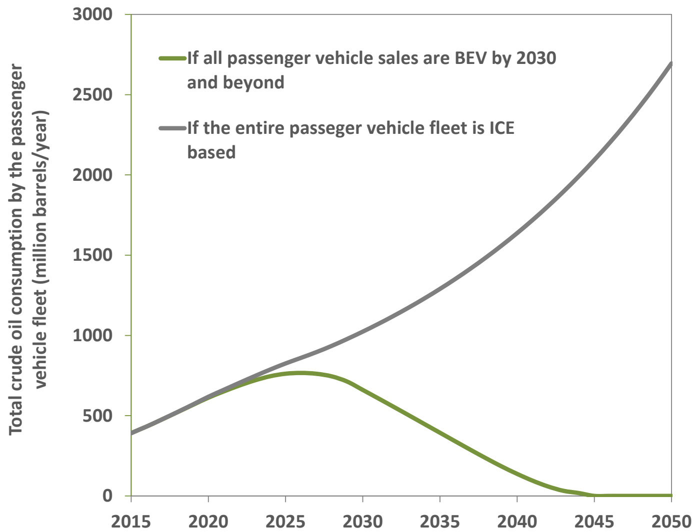
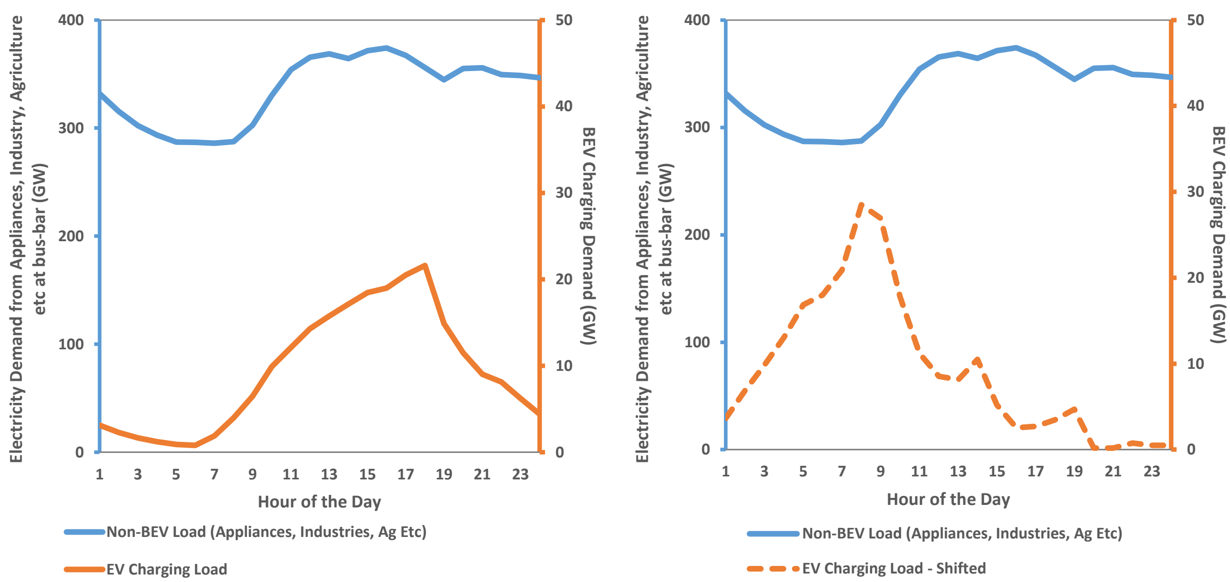


Figure 14: Total crude oil consumption by the passenger vehicle fleet (million barrels/yr)

3.6.Smart Charging Can Enable Cost-Effective RE Integration

BEV charging load could be shifted to a different time of day to reduce total system costs. Such load shifting is called smart charging. Figure 15 shows the average hourly BEV charging load with and without smart charging for the BAU scenario in May 2030.



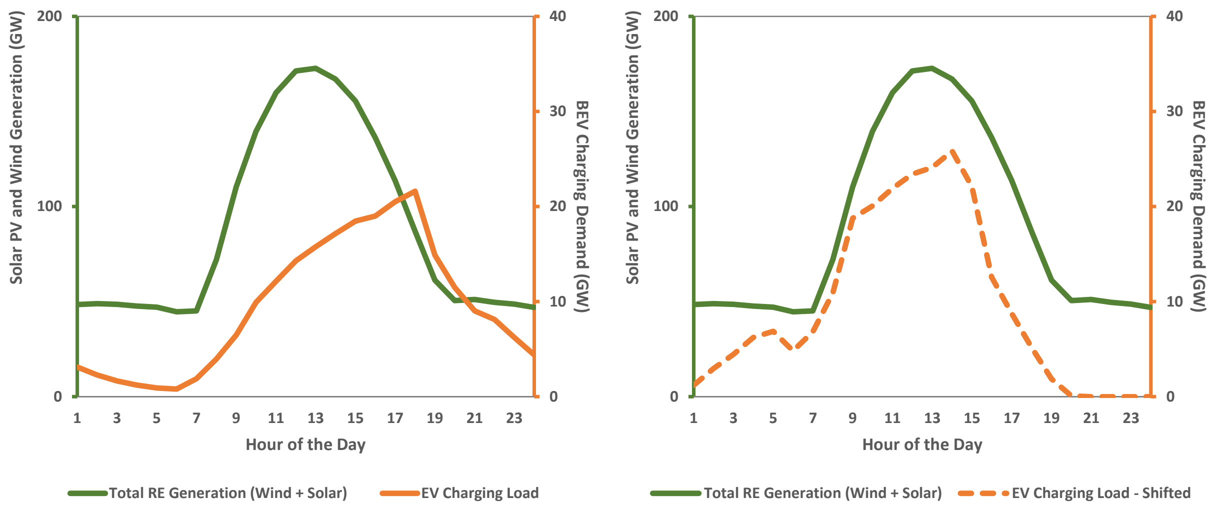
(a) Fixed Charging

(b) Smart Charging

Figure 15: Average hourly load curve and BEV charging load – BAU scenario (May 2030)

A large part of the charging load gets shifted to the early morning when the non-BEV electricity load is lowest and most of the electricity generation is coal based, i.e., least cost. Although this would increase the charging load's temporally explicit grid emission factor relative to the fixed-load case, the per-kilometer CO_2 emissions would still be lower for BEVs than for ICE vehicles. Also note that such large load shifting is made possible by the large number of two-wheelers with small batteries that make up the fleet. Since a two-wheeler can be fully charged within an hour and has high fuel efficiency, two-wheeler owners can move their charging to almost any hour of the day without affecting their trips.

Figure 16 shows the BEV charging profiles with and without smart charging for the NDC Compliant scenario in May 2030. The figure also shows the average hourly total RE generation (solar and wind).



(a) Fixed Charging **(b) Smart Charging**

Figure 16: Average hourly RE generation and BEV charging load – NDC Compliant scenario (May 2030)

The BEV charging load shifts almost entirely to the daytime to match the RE generation curve. This is primarily because significant daytime solar generation requires coal power plants to operate inefficiently at their technical minimum levels, or it requires RE curtailment; with smart charging, most of the BEV charging load shifts to avoid such curtailment or inefficient operation. Also, since most of the BEV charging occurs during RE generation hours, its temporally explicit grid emission factors are lower than in the fixed (non-smart) charging case.

Table 17 shows the impact of smart charging on generation capacity expansion and average cost of generation. In the BAU scenario, smart charging does not have any impact on the generation investments, but it would lower the average cost of generation by 0.7%. In the NDC Compliant scenario, smart charging can enable cost-effective RE integration in three ways. First, since the BEV charging load follows RE (especially PV) generation, significant RE curtailment could be avoided during the day. Second, smart charging would reduce the net load ramps[8] that the conventional capacity has to meet—especially around 6 or 7 PM when PV generation is dropping and evening electricity load is increasing. Third, smart charging can provide significant load reduction during the evening, so about 16 GW of coal generation capacity (Rs 100,000 Cr of total investment) could be avoided by 2030. As a result, with smart charging the reduction in the average generation cost would be 1.6% in the NDC Compliant scenario. Furthermore, smart charging can offer other ancillary services, including reserves or reactive power support through vehicle-to-grid mechanisms, which will be assessed in our future work.

Table 17: Generation capacity expansion (GW) and average cost of generation (Rs/kWh)

		BAU Scenario		NDC Compliant	
		Fixed BEV Charging	**Smart BEV Charging**	**Fixed BEV Charging**	**Smart BEV Charging**
Installed Capacity (GW)	Coal	420	420	361	345
	Gas	42	42	42	42
Average Cost of Generation (Rs/kWh)		2.93	2.90	3.04	2.99

4 Conclusion and Policy Implications

This report assesses the impact on a range of stakeholders of electrifying all passenger vehicle sales (cars and two-wheelers) in India by 2030. Between 2015 and 2030, the incremental capital cost of BEVs over ICE vehicles is expected to drop by over 60%–70%. BEV owners benefit when they switch from ICE vehicles, because the total incremental cost of BEVs is significantly lower than the annual fuel cost of ICE vehicles. Because the share of capital cost in the total incremental BEV cost drops from a high of 75% in 2015 to about 30% in 2030, the BEV owner's benefit is sensitive to the interest rate in the initial years; thus a BEV bulk procurement program with preferential financing (similar to Energy Efficiency Services Limited's appliance efficiency programs) is crucial for early adoption. Such programs could be run by a third party and—because of the significant benefits to BEV owners and the power sector—they might be financed entirely from power-sector revenue, rather than requiring government financial or fiscal support.

For vehicles with higher VKTs, BEVs are cost-effective even today, with annual benefits as high as Rs 20,000/yr by 2030. Since taxis (including shared-service vehicles such as Uber or Ola vehicles) have much higher VKTs than other passenger vehicles, they could be among the first candidates for BEV adoption. Moreover, they could be converted as a fleet, thereby significantly reducing

[8] Net load ramp is the hour-to-hour (or any time block) change in the load after integrating RE, i.e., load minus RE generation. The conventional generation capacity has to meet the net load in any system.

transaction and program-administration costs. However, access to public charging infrastructure would be crucial for such programs.

Despite aggressive vehicle electrification, the load added from BEV charging by 2030 is only 3.3% of the total electricity load in India (by energy). This is mainly because of the following three reasons: (a) In most urban areas of India, the rapid increase in electricity demand from numerous other end uses (particularly air conditioners) will be very large over the next 15–20 years, (b) the vehicle penetration by 2030 is dominated by two-wheelers that require much less energy than cars, and (c) the overall vehicle penetration is expected to be significantly lower than the penetration in other industrialized or emerging economies.

Although the additional load due to BEV charging is minor, it could still provide a valuable additional revenue source for the financially distressed distribution utilities. By 2030, the BEV charging load could earn about Rs 70,000 Cr/yr ($10 billion/yr) of additional revenue for utilities, which approximately equals the total utility financial deficit and the total government subsidy support to utilities in 2014, combined. One important assumption in this study is access to public charging infrastructure for all BEV owners, which could be a major challenge given the aggressive electrification levels. Deployment of such charging infrastructure could be financed using the additional revenue from BEV charging. Also, it is likely that BEV adoption, especially in the initial years, would be limited to a few major urban centers. Although the incremental BEV charging load is minor at the national level, its impacts on local distribution networks, especially in potential hotspots, could be significant. The problem may worsen (or subside, depending on whether BEVs have smart-charging capability) if the BEV hotspots coincide with PV hotspots and may require significant distribution system upgrades. Analyzing such local distribution system impacts is important, and it is part of our future work.

BEVs have significantly lower per-kilometer CO_2 emissions than do ICE vehicles. In the NDC Compliant scenario, BEVs reduce emissions by over 40%–50% for cars (vans, compact sedans, and subcompact hatchbacks) and over 50% for two-wheelers. Even if we assume that no decarbonization measures in the BAU plan materialize and the grid in 2030 remains as coal heavy as it was in 2015, BEVs still reduce per-kilometer CO_2 emissions by 20%–30% for cars and about 30% for two-wheelers. If the NDC Compliant efforts of grid decarbonization continue beyond 2030, passenger transport electrification alone can lower CO_2 emissions by about 600 million tons/yr by 2050 (8% of India's total GHG emissions by 2050). If the clean power targets become more ambitious in the future, even more emissions reductions are possible from the transport sector.

BEVs can also avoid significant crude oil imports in India. By 2030, BEVs can avoid importing 360 million barrels/yr (16% of total crude oil consumption in 2030) and, by 2050, nearly 2,695 million barrels/yr (60% of total). Assuming a conservative crude oil price of $40/barrel, the total reduction in the oil import bill would be about $14 billion/yr by 2030 and $100 billion/yr by 2050.

With smart charging, BEVs could reduce the total cost of electricity generation. In the BAU scenario, smart charging does not have any impact on generation investments, but it would lower the average cost of generation by 0.7%. In the NDC Compliant scenario, smart charging can enable cost-effective RE integration in three ways. First, since the BEV charging load follows RE (especially PV) generation, significant RE curtailment could be avoided during the day. Second, smart charging would reduce the net load ramps that the conventional capacity has to meet—especially around 6 or 7 PM when PV generation is dropping and the evening electricity load is increasing. Third, smart charging can provide significant load reduction during the evening, so about 16 GW of coal generation capacity (Rs 100,000 Cr of total investment) could be avoided by 2030. As a result, with smart charging, the reduction in the average generation cost would be 1.6% in the NDC Compliant scenario. Furthermore, smart charging can offer several other ancillary services, including reserves or reactive power support through vehicle-to-grid mechanisms, which will be assessed in our future work.

Deploying public charging infrastructure for BEVs and enabling smart charging would involve additional costs. Based on the experience of appliance-level demand response and smart control technologies, the additional cost of enabling smart charging, especially for private BEV chargers, would be minor (Shah, Abhyankar, Phadke, & Ghatikar, 2015). The cost for deploying the public charging infrastructure could involve substantial capital investments, especially by electric utilities. However, quantifying such additional investments is outside the scope of this report and will be evaluated in our future work.

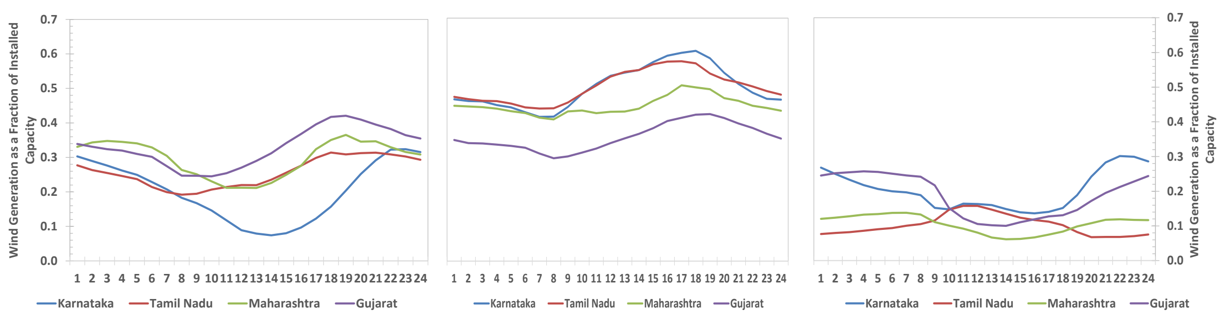
Appendix 1: Assumptions for Power System Modeling

5.1 Hourly PV and Wind Generation Forecast by Region

5.1.1 Wind Generation Profiles

India's current wind installed capacity is more than 21 GW and has been growing consistently over the last 10 years or so. Indian wind energy generation is highly seasonal and peaks during monsoon. For fiscal year (FY) 2030, we have forecasted the hourly profiles of wind energy generation using historical generation data for FYs 2010–2013 from the states of Tamil Nadu, Karnataka, Maharashtra, and Gujarat. These states together cover over 80% of the existing wind installed capacity and over 75% of the total wind potential in India (CWET, 2014; Phadke, 2012). Hourly wind generation data was sourced from the websites of the respective state load dispatch centers. The reported wind generation does not account for curtailment, so the data may not represent the true profiles of wind generation. Unfortunately, data on the exact amount and timing of curtailment are not available. Industry experts suggest that wind energy curtailment was minor until FY 2012–2013 (Phadke, Abhyankar, & Rao, 2014).

Figure **17** shows the seasonal averages of wind energy generation (as a share of installed capacity) in the key states mentioned above. There is significant seasonal variation in wind generation in all states. Wind generation peaks in monsoon (June through September) and drops significantly in the winter. However, the diurnal pattern of wind generation in a season is very similar across all states. In monsoon and summer, wind generation peaks in late afternoon or early evening, which matches with the overall demand patterns in these seasons.



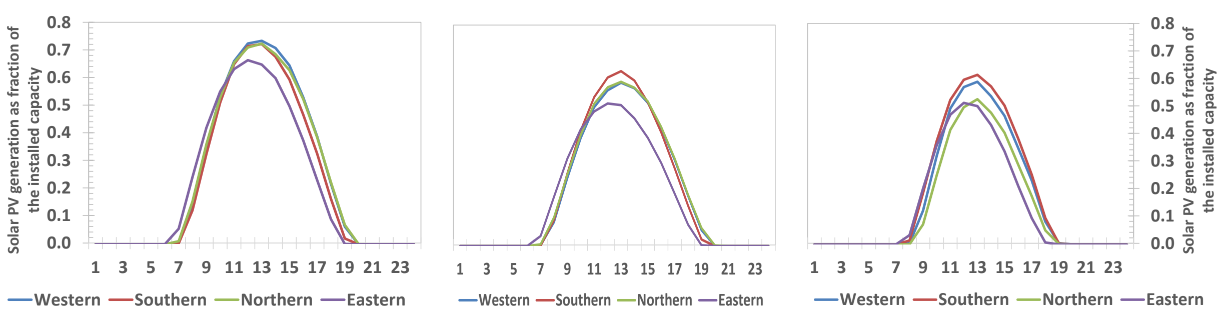
Summer (April–May) Monsoon (June–September) Winter (December–February)

Figure 17: Average daily wind generation curve (of existing capacity) in key states

For future wind capacity addition, we use the wind energy potential numbers in each state from our previous study of wind energy potential in India (Phadke, 2012). For estimating the hourly wind generation profile for a future year (2030, in this case), the approach in other studies has been to use time-series data from meso-scale models. But in this study, we are scaling actual generation data for the current year, which assumes that the additional capacity will be installed in the same regions and hence will have the same profiles. In reality, capacity addition will occur in different areas, which is likely to reduce the overall variability of wind generation at the regional level owing to geographic diversity of the wind installations. However, given that verified hourly wind resource data are not available in the public domain, we could not use wind resource data from undeveloped sites. Thus, wind variability in this analysis would be high and the capacity value conservative; this could be seen as the worst-case scenario for future wind capacity additions. More detailed analysis (for example using time-series meso-scale resource data) is needed to improve the profiles of wind generation used in this analysis.

5.1.2 Solar PV Generation Profiles

Total grid-connected PV capacity in India is only 3 GW (2015), although it is increasing rapidly given the dropping costs and favorable regulatory and policy environments. The largest capacity (1.5 GW) is operational in the state of Gujarat. However, several studies have shown practically infinite solar energy potential in India. For estimating the hourly generation profile, we use 100 sites spread over all five regions with the best quality solar resource (measured in direct normal irradiance and global horizontal irradiance, kWh/m^2) using the national solar energy dataset for India developed by the National Renewable Energy Laboratory, which contains hourly irradiance data for every 5 km x 5 km grid in India. We feed the solar irradiance data into the System Advisor Model also developed by the National Renewable Energy Laboratory, to get the PV output at the chosen 100 sites. The hourly PV output profiles of the sites in each region are averaged to arrive at the regional PV generation profile. The average generation profiles for each season are shown in Figure 18.



Summer (April–May) Monsoon (June–September) Winter (December–February)

Figure 18: Average daily Solar PV generation curves for each region

The solar resource peaks in the summer and drops in the winter, but the seasonal variation is not as dramatic as it is for wind. It may appear that there is not much difference in the average resource quality of the western, northern, and southern regions; however, resource quality would vary significantly at the individual site level. Most of India's best quality solar resource is concentrated in the western and northern regions. Note that averaging solar profiles over multiple sites may underestimate the total variability in PV generation. On the other hand, as explained in the previous section on wind energy, we assume that future PV capacity is added at the sites selected for estimating the hourly generation profile. This may not fully capture the benefits of geographic diversity and may overestimate variability to some extent. A comprehensive Geographic Information Systems analysis for site selection would correct these errors, but that is outside the scope of this research.

5.2 Operational Parameters of Generators

Table 25 in Appendix 2 summarizes our assumptions for the operational characteristics (unit size, heat rates, ramp rates, minimum stable level, etc.) of the power plants. We estimate the values using actual hourly dispatch data, actual outage and other performance data, regulatory orders on heat rates and costs, other relevant literature, and actual practices in India. Currently, the combined-cycle (gas) plants in India are not operated in the open-cycle mode (gas turbine only; no waste heat recovery). However, we assume that, by 2030, the gas turbines in the combined-cycle plants could be operated independently in open-cycle mode, which enhances the system flexibility considerably.

5.3 Hydro Capacity and Energy Model

Hydro capacity is modeled using a fixed monthly energy budget. Based on the historical dispatch and minimum flow and spill constraints, we estimate the capacity factors of the hydro power plants for every month. Subject to such monthly capacity factor constraints, reservoir-based hydro power plants are assumed to be optimally dispatched. Table 18 shows the monthly capacity factors for hydro plants in each region. Hydro capacity factors depend on a variety of factors including high recharge season (such as summer or monsoon), irrigation and minimum flow requirements, and so forth.

Table 18: Monthly capacity factors of hydroelectric projects in each region

	East	Northeast	West	South	North
January	18%	25%	30%	28%	24%
February	18%	23%	27%	32%	29%
March	19%	22%	26%	40%	36%
April	25%	34%	26%	31%	40%
May	18%	49%	26%	27%	62%
June	27%	61%	23%	27%	64%
July	28%	80%	27%	31%	67%
August	27%	83%	47%	37%	67%
September	32%	67%	49%	54%	71%
October	26%	60%	38%	39%	40%
November	16%	40%	26%	29%	29%
December	8%	26%	21%	24%	26%
Annual Average	***22%***	***47%***	***30%***	***33%***	***46%***

Sources: (CEA, 2015b, 2015a)

More than 50% of India's current hydro capacity is run on rivers; output of run-of-the-river plants is assumed to be flat subject to the monthly capacity factor constraint. India has limited pumped storage capacity; it is modeled using a weekly energy balance, i.e., the head and tail storage ponds return to their initial volumes at the end of each week. We ran a sensitivity case with daily energy balance, but, given the small pumped storage capacity, it does not make a large difference to the overall results.

5.4 Costs

Table 19 shows the assumptions for capital and fixed O&M cost for each technology. The current capital costs of renewable technologies are from CERC's tariff regulations 2015. CERC's tariff regulations for the conventional projects do not mention the capital cost norms. For coal-based power projects, we use CERC's interim order (2012) on benchmarking the capital costs of thermal projects (CERC, 2012). For gas, diesel, and hydro projects, we use industry norms per our previous report (Abhyankar et al., 2013a). Capital and O&M costs of the nuclear projects are from (Ramana et al., 2005).

Table 19: Capital cost (overnight; excluding interest during construction) and fixed O&M cost of generating plants (2015 Rs)

Generation Technology	Capital Cost Rs Cr/MW (2015)	Fixed O&M Cost Rs Cr/MW/yr (2015)	Fixed O&M Cost as % of Capital Cost
Coal (> 600-MW units)	5.37	0.14	2.7%
Coal (500-MW units)	5.08	0.16	3.1%
Gas CCGT (combined cycle)	4.80	0.15	3.1%
Gas Combustion Turbine (open cycle)	4.20	0.15	3.5%
Diesel	3.60	0.13	3.5%
Nuclear	5.71	0.11	2.0%
Hydro (< 200 MW)	8.00	0.32	4.0%
Hydro (> 200 MW)	8.00	0.20	2.5%
Small Hydro (5–25 MW) - excluding Himachal Pradesh, Uttaranchal, and Northeastern States	5.93	0.17	2.8%
Small Hydro (5–25 MW) – Himachal Pradesh, Uttaranchal, and Northeastern States only	7.54	0.21	2.8%
Biomass (for rice straw and juliflora based projects with water-cooled condenser)	6.10	0.45	7.3%
Wind (onshore)	6.19	0.11	1.7%
Solar PV	5.87	0.13	2.2%

Sources: (Abhyankar et al., 2013a; CERC, 2012, 2014, 2015; Ramana et al., 2005)

Note that the capital cost of coal units shown above does not include the additional investment needed to meet the new norms for particulate matter, sulfur oxides, and nitrogen oxides emissions (2015); such investments may increase the capital cost of the coal units by over 10%.

The assumed economic life of all generation assets is 25 years, and the weighted-average cost of capital is assumed to be 12.8%, i.e., weighted average of the 14% return on equity (ROE) and 10% interest rate assuming a debt-to-equity ratio of 70:30.

The PV cost in the CERC regulations matches the prices quoted in the latest PV reverse auctions in India. In the state of Madhya Pradesh, a reverse auction concluded in July 2015 received a winning bid of Rs 5.05/kWh (Business Standard, 2015). Using CERC's capital cost and O&M cost norms, a weighted-average cost of capital of 12.8%, and a capacity factor of 21%, the levelized cost of electricity for a PV plant is Rs 5.07/kWh.

Because most of the conventional technologies have already matured, their capital costs are not assumed to change through 2030. Renewable technologies, especially PV, still have high learning rates, and thus we assume their costs decline between 2015 and 2030 (Table 20).

Table 20: Wind and PV future capital cost reductions

	2015 Capital Cost Rs Cr/MW	Average Annual Price Reduction (%)	2030 Capital Cost Rs Cr/MW
Wind	6.19	-	6.19
PV	5.87	4.7%	2.85

For PV, we use the capital cost trajectory projected in the *Global PV Market Outlook 2015* (BNEF, 2015). Based on these capital cost projections, we estimate the average annual reduction in PV prices to be 4.7% between 2015 and 2020. We apply the same annual reduction up to 2030. Lawrence Berkeley National Laboratory's U.S. PV market assessment reports similar cost reductions (Barbose, Weaver, & Darghouth, 2014). For wind, we use historical U.S. capital cost data from Lawrence Berkeley National Laboratory's wind technologies assessment report (Wiser & Bolinger, 2015). Although there have been significant annual fluctuations in wind capital cost, the capital cost has not changed much over the last 10 years or so.[9] Therefore, we assume that wind capital cost stays the same until 2030.

[9] Wind power-purchase agreement (PPA) prices have dropped significantly in recent years. In 2014, the average levelized wind PPA price in the United States was $23/MWh including the Production or Investment Tax Credits (Wiser & Bolinger, 2015). If the tax credits are excluded, the levelized price is about $40/MWh (approximately Rs 2.5/kWh).

5.5 Fuel Availability and Prices

Domestic gas and coal availability is constrained in India (Table 21). Coal availability for the power sector is from the Ministry of Coal's projections in the 12th 5-year plan up to 2017; we project the same trend up to 2030. Domestic gas availability is highly constrained too, and several gas-based power plants are stranded because gas is unavailable. We assume that future domestic gas availability for the power sector remains the same as the current quantity. If the system needs more natural gas, it will have to be imported as liquefied natural gas (LNG) at international prices. We do not assume any restrictions on imported coal and gas or on other fuels such as diesel and biomass.

Table 21: Fuel availability and calorific value assumptions

Fuel	Max Availability in FY 2030	Gross Calorific Value
Domestic Coal	1,071 million tons/yr	4,000 kCal/kg
Imported Coal	Unlimited	5,400 kCal/kg
Domestic Gas	29 bcm/yr	9,000 kCal/m^3
Imported LNG	Unlimited	9,000 kCal/m^3
Diesel	Unlimited	10,000 kCal/L
Biomass	Unlimited	3,000 kCal/kg

Source for coal and gas availability: (Planning Commission, 2012)

Domestic coal price data are from Coal India Limited's (CIL's) annual reports as the average price of coal sold by CIL in that year (CIL, 2011, 2015).[10] Historical trends in imported coal prices are from the BP Statistical Review (Asian marker price) (BP, 2015). The domestic natural gas price is from the Ministry of Petroleum and Natural Gas' orders in various years/months. The imported LNG price for the current year (2015) is from media reports on the international LNG market, while the historical trend in imported LNG price in India is from (Sen, 2015). The fuel prices are assumed to increase at the long-run (10-year) CAGR. However, the historical fuel prices are listed in nominal dollars (or rupees, as the case may be). To assess the price trend in real terms, we deflate the nominal prices using the annual inflation rate (Wholesale Price Index), sourced from (OEA, 2015). Table 22 shows the current fuel prices, long-run nominal and real growth rates, and projected 2030 fuel prices expressed as 2015 dollars or rupees.

[10] CIL controls more than 80% of India's total coal production, and about 80% of its coal is sold to the power sector.

Table 22: Fuel price assumptions

Fuel	Fuel Price in 2015 (FOB)	Escalation in Nominal Price (10-yr CAGR) %	Inflation Adjusted (Real) Escalation % p.a.	Fuel Price in 2030 (FOB)
Domestic Coal (Rs/ton)	1,948	7.5%	1.4%	2,400
Imported Coal ($/ton)	77.89	6.9%	0.7%	86
Domestic Gas ($/mmbtu)	4.66	8.8%	2.7%	6.9
LNG ($/mmbtu)	11	6.2%	0.1%	11

Sources: (BP, 2015; CIL, 2011, 2015; OEA, 2015; Sen, 2015)

Note: All price and cost numbers refer to 2015 real values.

Note that these are the FOB (free on board) prices and do not include fuel transportation and LNG regasification costs and so forth. Those costs depend on the locations of the plant and the fuel sources. Domestic coal transportation costs are from regulatory proceedings and tariff orders of the state and central generation utilities. Imported coal plants are assumed to be located on the shore and therefore would not incur any domestic transportation charge, except in the northern and eastern regions. Table 23 shows the coal transportation costs to each of the regions.

Table 23: Average coal transportation costs to each region

	Domestic Coal (Rs/ton)	Imported Coal	
		International Transportation ($/ton)	Domestic Transportation (Rs/ton)
North	1,200	30	1,500
West	1,500	30	-
South	1,800	30	-
East	1,000	30	1,500

Source: Authors' estimates, regulatory filings

Note: All price and cost numbers refer to 2015 real values.

Similarly, imported LNG-based plants are not assumed to incur domestic gas pipeline charges, except in the northern and eastern regions; all LNG imports are assumed to incur a regasification cost of $0.5/mmbtu. In the case of domestic gas, we assume two sources: (a) Bombay high field (off the western coast) near Mumbai and, (b) KG-D6 field off the eastern coast near Andhra Pradesh. Table 24 shows the gas transportation costs to each of the regions.

Table 24: Average gas transportation costs to each region

	Domestic Gas ($/mmbtu)		Imported LNG ($/mmbtu)		
	Bombay High	KG D-6	International Transportation	Regasification	Domestic Pipeline
North	1.5	2.0	1.0	0.5	1.5
West	0.5	1.5	1.0	0.5	0
South	1.5	0.5	1.5	0.5	0
East	N/A	1.5	1.5	0.5	1.5

Data source: Authors' estimates, Petroleum and Natural Gas Regulatory Board (PNGRB) website.

Note: All price and cost numbers refer to 2015 real values.

5.6 Transmission

In 2013, the southern regional grid in India was integrated with the northern regional grid. Additionally, significant transmission investments have been planned for the near future. Going forward, we assume no constraints on transmission.

Appendix 2: Assumptions for Operational Characteristics of Generating Plants

Table 25: Assumptions for operational characteristics of generating plants

Generator Technology	Region	Generator_Name	Average Unit Size (MW)	Min Stable Factor (%)	Gross Heat Rate (GJ/MWh)	Start Cost ($)	Shutdown Cost ($)	Min Up Time (hrs)	Min Down Time (hrs)	Max Ramp Up (MW/min.)	Max Ramp Down (MW/min.)	Auxiliary Consumption (%)	Planned Maintenance Rate (%)	Forced Outage Rate (%)
Biomass+Cogen	East	ER_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Biomass+Cogen	North	NR_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Biomass+Cogen	South	SR_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Biomass+Cogen	West	WR_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Coal	East	ER_Old_<210	87	55	12	8741	8741	24	24	0.87	0.87	10.6	12.3	32.9
Coal	East	ER_Old_210/250	220	55	11.2	22000	22000	24	24	2.2	2.2	9	2.8	11.9
Coal	East	ER_Old_500/600	516	55	10.8	51579	51579	24	24	5.16	5.16	6.5	4.9	11.8
Coal	East	ER_Old_660	660	55	10	66000	66000	24	24	6.6	6.6	8.1	5	11.8
Coal	East	ER_Old_Other	390	55	11	39000	39000	24	24	3.9	3.9	10.5	0.9	18.6
Coal	East	ER_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Coal	North_East	NER_Old	30	0	12	3000	3000	24	24	0.3	0.3	10.6	0	100
Coal	North	NR_Old_<210	114	55	12.2	11378	11378	24	24	1.14	1.14	10.6	13.3	14
Coal	North	NR_Old_210/250	222	55	11.4	22238	22238	24	24	2.22	2.22	9	3.6	8.4
Coal	North	NR_Old_500/600	531	55	10.8	53077	53077	24	24	5.31	5.31	6.5	5.5	5
Coal	North	NR_Old_660	660	55	9.7	66000	66000	24	24	6.6	6.6	8.1	5	5
Coal	North	NR_Old_Other	348	55	10.8	34750	34750	24	24	3.48	3.48	10.5	1.2	19.2
Coal	North	NR_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Coal	South	SR_Old_<210	99	55	12.2	9925	9925	24	24	0.99	0.99	10.6	3.7	10.9
Coal	South	SR_Old_210/250	215	55	11.4	21455	21455	24	24	2.15	2.15	9	5.6	5.7
Coal	South	SR_Old_500/600	512	55	10.8	51176	51176	24	24	5.12	5.12	6.5	3.7	3.5
Coal	South	SR_Old_660	660	55	9.7	66000	66000	24	24	6.6	6.6	8.1	5	3.5
Coal	South	SR_Old_Other	300	55	10.8	30000	30000	24	24	3	3	10.5	8.2	8.6
Coal	South	SR_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Coal	West	WR_Old_<210	106	55	12.2	10603	10603	24	24	1.06	1.06	10.6	6.1	22.9
Coal	West	WR_Old_210/250	220	55	11.4	21968	21968	24	24	2.2	2.2	9	6	7.2
Coal	West	WR_Old_500/600	505	55	10.8	50500	50500	24	24	5.05	5.05	6.5	3.6	4.3
Coal	West	WR_Old_660	774	55	9.7	77429	77429	24	24	7.74	7.74	8.1	0	15.4
Coal	West	WR_Old_Other	312	55	10.8	31200	31200	24	24	3.12	3.12	10.5	1.3	10.8
Coal	West	WR_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Diesel	East	ER_Diesel	17.2	0	13.5	100	100			17.2	17.2	1	5	5

Generator Technology	Region	Generator_Name	Average Unit Size (MW)	Min Stable Factor (%)	Gross Heat Rate (GJ/MWh)	Start Cost ($)	Shutdown Cost ($)	Min Up Time (hrs)	Min Down Time (hrs)	Max Ramp Up (MW/min.)	Max Ramp Down (MW/min.)	Auxiliary Consumption (%)	Planned Maintenance Rate (%)	Forced Outage Rate (%)
Diesel	North_East	NER_Diesel	60	0	13.5	100	100			17.2	17.2	1	5	5
Diesel	North	NR_Diesel	13	0	13.5	100	100			13	13	1	5	5
Diesel	South	SR_Diesel	50	0	13.5	100	100			50	50	1	5	5
Diesel	West	WR_Diesel	17.5	0	13.5	100	100			17.5	17.5	1	5	5
Gas_CCGT	East	ER_CC_GT	25	10	12	250	250	1	1	2.5	2.5	1	5	5
Gas_CCGT	East	ER_CC_ST	11	40	14	1100	1100	6	6	0.04	0.04	5	10	10
Gas_CCGT	North_East	NER_CC_GT	21	10	12	214	214	1	1	2.14	2.14	1	5	5
Gas_CCGT	North_East	NER_CC_ST	11	40	14	1100	1100	6	6	0.04	0.04	5	10	10
Gas_CCGT	North	NR_CC_GT	79	10	12	794	794	1	1	7.94	7.94	1	5	5
Gas_CCGT	North	NR_CC_ST	106	40	14	10589	10589	6	6	0.39	0.39	5	10	10
Gas_CCGT	South	SR_CC_GT	85	10	12	852	852	1	1	8.52	8.52	1	5	5
Gas_CCGT	South	SR_CC_ST	84	40	14	8380	8380	6	6	0.31	0.31	5	10	10
Gas_CCGT	West	WR_CC_GT	155	10	12	1552	1552	1	1	15.52	15.52	1	5	5
Gas_CCGT	West	WR_CC_ST	112	40	14	11250	11250	6	6	0.41	0.41	5	10	10
Gas_CT	East	ER_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	North_East	NER_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	North	NR_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	South	SR_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	West	WR_CT	50	10	12	0	0	1	1	5	5	1	5	5
Hydro_Large	East	ER_Hydro_<=100	50	0	0	0	0			5	5	1	5	5
Hydro_Large	East	ER_Hydro_>100	150	0	0	0	0			15	15	1	5	5
Hydro_Large	North_East	NER_Hydro_<=100	29	0	0	0	0			2.9	2.9	1	5	5
Hydro_Large	North_East	NER_Hydro_>100	139	0	0	0	0			13.9	13.9	1	5	5
Hydro_Large	North	NR_Hydro_<=100	60	0	0	0	0			6	6	1	5	5
Hydro_Large	North	NR_Hydro_>100	163	0	0	0	0			16.3	16.3	1	5	5
Hydro_Large	South	SR_Hydro_<=100	29	0	0	0	0			2.9	2.9	1	5	5
Hydro_Large	South	SR_Hydro_>100	118	0	0	0	0			11.8	11.8	1	5	5
Hydro_Large	West	WR_Hydro_<=100	44	0	0	0	0			4.4	4.4	1	5	5
Hydro_Large	West	WR_Hydro_>100	154	0	0	0	0			15.4	15.4	1	5	5
Hydro_Small	East	ER_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	North_East	NER_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	North	NR_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	South	SR_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	West	WR_SmallHydro	20	0	0	0	0			20	20	1	5	5
Pumped Storage	East	ER_Hydro_PS	163	0	10	0	0			16.3	16.3	1	5	5
Pumped Storage	North_East	NER_Hydro_PS	142	0	10	0	0			14.2	14.2	1	5	5
Pumped Storage	North	NR_Hydro_PS	142	0	10	0	0			14.2	14.2	1	5	5

Generator Technology	Region	Generator_Name	Average Unit Size (MW)	Min Stable Factor (%)	Gross Heat Rate (GJ/MWh)	Start Cost ($)	Shutdown Cost ($)	Min Up Time (hrs)	Min Down Time (hrs)	Max Ramp Up (MW/min.)	Max Ramp Down (MW/min.)	Auxiliary Consumption (%)	Planned Maintenance Rate (%)	Forced Outage Rate (%)
Pumped Storage	South	SR_Hydro_PS	130	0	10	0	0			13	13	1	5	5
Pumped Storage	West	WR_Hydro_PS	142	0	10	0	0			14.2	14.2	1	5	5
Run of River	East	ER_Hydro_ROR	48	0	0	0				4.8	4.8	1	5	5
Run of River	North_East	NER_Hydro_ROR	63	0	0	0				6.3	6.3	1	5	5
Run of River	North	NR_Hydro_ROR	68	0	0	0				6.8	6.8	1	5	5
Run of River	South	SR_Hydro_ROR	21	0	0	0				2.1	2.1	1	5	5
Run of River	West	WR_Hydro_ROR	46	0	0	0				4.6	4.6	1	5	5
Nuclear	East	ER_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10
Nuclear	North	NR_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10
Nuclear	South	SR_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10
Nuclear	West	WR_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10

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